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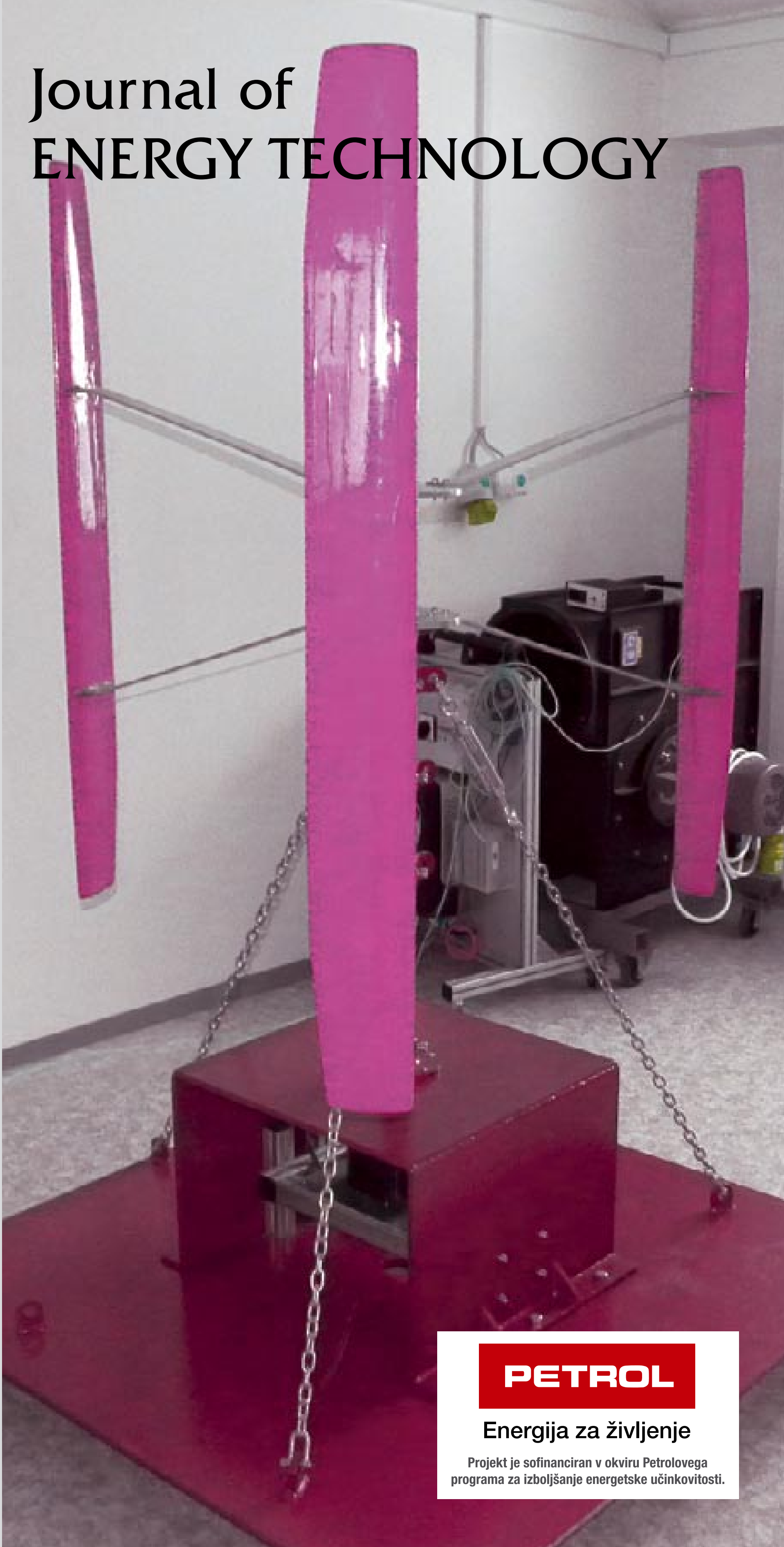

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Sofinanciranje energetske prenove javnih stavb v Sloveniji

Pravi balzam za gradbeno sušo v Sloveniji je drugi javni razpis Ministrstva za infrastrukturo in prostor RS za sofinanciranje energetske sanacije javnih objektov (vrtcev, šol, zdravstvenih domov, knjižnic, ...) v lasti lokalnih skupnosti v višini 47,6 milijona evrov. Ti obnovitveni projekti pomenijo za gradbena podjetja, industrijo gradbenega materiala in proizvajalce opreme več dela in s tem lajšanje kriznih časov.

Naložbe v energetsko sanacijo stavb imajo dolgoročen in večstranski učinek, ker gre za delovno intenzivne investicije, kar pomeni, da ob sami izvedbi investicije ustvarimo še nova delovna mesta, povečamo proizvodnjo gradbenega materiala in seveda prihranimo na energentih. Žal razpisani znesek predstavlja le majhen del potrebnega prometa gradbenih podjetij, ki naj bi na letnem nivoju znašal okrog 1,5 milijarde evrov. Razpisani znesek tako predstavlja le okrog 5 odstotkov potrebnega prometa v gradbeništvu.

Vendar samo energetska sanacija objektov sčasoma ne bo več dovolj. Lep zgled je npr. Francija, kjer so z letošnjim letom zaostrili predpise glede porabe primarne energije na največ 50 kilovatnih ur po kvadratnem metru stavbe na letnem nivoju (50 kWh/m^2/leto). Ta zaostritev je trikrat nižja od tiste, ki so jo dopuščali stari predpisi izpred sedmih let. Zanimiva je tudi zahteva v novih predpisih, ki narekuje najmanj sedemnajst odstotkov zastekljenih površin po kvadraturi stavbe. To pomeni na sto kvadratnih metov uporabne površine stavbe vsaj sedemnajst kvadratnih metrov steklenih površin. S tem predpisom želijo vzpodbuditi predvsem pasivni energetski del izkoriščanja sončne energije za ogrevanje stavb. A to hkrati pomeni večjo toplotno obremenitev stavb v poletnem času. To pomeni, da se bo razvoj stekla in stavbnega pohištva (oken) moral prilagoditi novim zaostrenim energetskim zahtevam. Temperaturno področje v našem podnebnem pasu se giblje od -30°C do +35°C, kar znaša cca. 65°C temperaturne diference. Toplotna prevodnost današnjih dvo-slojnih stekel in oken, ki znaša 1,1 W/m^2K, za nove zahteve tako ne bo več zadoščala. Za to bo primernejša tro-slojna zasteklitev s toplotno prevodnostjo 0,6 W/m^2K. Pri tem pa bo potrebno rešiti še nevarnost kondenzacije zračne vlage na zunanjem steklu tro-slojne zasteklitve. Danes se to rešuje s tanko-plastnimi nanosi kovinskih oksidov na zunanji strani zunanjega stekla, ki preprečujejo izpust infrardečega toplotnega sevanja iz notranjosti stavbe v okolje.

Razvoj novih zasteklitev, vključno s kombinacijo prosojnih foto-voltaičnih modulov kot steklenih delov stavb, bo s temi novimi predpisi v Franciji, ki jim bodo verjetno sledile tudi druge države, še pospešen.

Krško, avgust 2013

Andrej PREDIN

Co-financing of energy renovation of public buildings in Slovenia

One remedy for the building construction drought in Slovenia is the second invitation of the Ministry of Infrastructure RS to the co-financing of energy renovation of public facilities (kindergartens, schools, health centres, libraries, etc.) owned by the local communities, to the amount of 47.6 million euros. These projects represent recovery for construction companies, industry, building material and equipment manufacturers, and more work, and thus relieve the effects of the crisis.

Investments in energy efficiency renovation have long-term and multifaceted effects; because it is labour-intensive investment, its essence is to create more jobs, to increase the production of building materials and, of course, to save on energy. Unfortunately, the modest tendered amount represents only a small fraction of the needs of construction companies in Slovenia, which are assessed as needing €1.5 billion on an annual basis. Therefore, the tendered amount represents only about 5 percent of the needed yearly funds.

However, the energy renovation of buildings alone will no longer suffice. A good example of this can be found in France, which this year tightened rules on primary energy consumption to a maximum of 50 kilowatt hours per square meter of the building per year (50 kWh/m²/year); this is a mere third of what the previous regulations of seven years ago permitted. Also interesting is the new requirement that at least seventeen percent of the exterior surface of a new building be glass. This aims to encourage passive solar energy for heating buildings, but it also means greater heat loads in the summer. Consequently, the development of glass and windows has to adapt to the new stringent energy requirements.

The temperature range in Slovenia's climate zone is from -30 to +35 degrees or about 65 degrees difference. The thermal conductivity of current two-parallel glass windows is 1.1 W/m²K, which will no longer be enough for the new requirements. A new standard must be more efficient: triple-layer glass with a thermal conductivity of 0.6 W/m²K. For this, we will need to resolve the danger of condensation on the outer glass surface of triple-layer glass. Today, this is addressed by a thin coating of metal oxides on the outer side of the outer glass pane, preventing the release of infrared radiation (heat) from the interior of the building to the outside environment.

The development of new glass and windows including a combination of transparent photovoltaic modules will be encouraged by these new regulations in France, which are expected to be followed by other countries.

Krško, August, 2013

Andrej PREDIN

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HYDROGEN TECHNOLOGIES IN A SELF-SUFFICIENT ENERGY SYSTEM WITH RENEWABLES

VODIKOVE TEHNOLOGIJE V SAMOZADOSTNEM ENERGETSKEM SISTEMU Z OBNOVLJIVIMI VIRI ENERGIJE

Rok Lacko[ℜ], Boštjan Drobnič, Miran Leban

Keywords: experimental evaluation of numerical model, hydrogen technologies, reference household, renewable energy sources, self-sufficient energy system

Abstract

A potential solution for stand-alone power generation is to use hybrid energy systems with hydrogen energy storage. In this paper, a pre-feasibility study of using a 100% renewable hybrid energy system (solar and wind energy source) with hydrogen technologies (electrolyser, hydrogen tank, fuel cell) for a reference household application in Portorož, Slovenia is examined and explained. The HOMER software tool is used for simulations and optimal energy system identification, in which geographical location and availability of energy sources, load dynamics, component technical and economical characteristics are considered. The experimental work was performed on existing laboratory facilities with hydrogen technologies. The optimal feasible system capacity (34 kW), with the lowest total net present value (€138,452), is approximately eight times larger than peak power demand (3,8 kW). Experiments confirmed adequate numerical model design with an only 3% deviation in results.

Povzetek

Uporaba hibridnih energetskih sistemov s hranjenjem energije v obliki vodika predstavlja možno rešitev samozadostne preskrbe z energijo. V tem prispevku je predstavljena numerična analiza in eksperimentalna evalvacija električne preskrbe referenčnega gospodinjstva v Portorožu

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izključno na osnovi obnovljivih virov energije (sonce, veter) in z uporabo vodikovih tehnologij (elektrolizer, plinohram, gorivna celica). Za simulacijo obratovanja in določitev optimalne konfiguracije energetskega sistema je bilo uporabljeno programsko okolje HOMER, za eksperimentalno delo pa obstoječi demonstracijski laboratorij z vodikovimi tehnologijami. Optimalna rešitev je izbrana z upoštevanjem geografske lokacije in razpoložljivosti virov energije, dinamiko porabe električne energije ter tehnoloških in ekonomskih značilnosti posameznih komponent. Optimalni energetski sistem z najnižjo neto sedanjo vrednostjo projekta (138.452 €) potrebuje za pokritje električne porabe skoraj 8-krat večjo (34 kW) nazivno moč tehnologij obnovljivih virov od maksimalne konične moči (3,8 kW). Eksperimentalno obratovanje potrjuje ustreznost numeričnega modela, saj je razlika v rezultatih majhna (3 %).

1 INTRODUCTION

Meeting increasingly stringent environmental standards is often achieved by increasing the share of intermittent renewable energy sources (RES) in an energy system. Due to the misalignment of energy production and demand, the use of energy storage is usually required, [1]. The use of renewables, coupled with hydrogen (storage) technology, is a viable solution, [2–4]. Furthermore, hydrogen technologies can also be used in a variety of hybrid energy systems, including biomass-based energy systems, [5], and integrated gasification combined cycle plants with CO2 capture, [6].

The following technical and economic analyses of RES energy systems with hydrogen storage have already been discussed: modelling stand-alone applications [2], [7–13], modelling integrated or grid connected applications [14–17] and operational experience, [18].

An RES-hydrogen energy system for a self-sufficient household is described in this study, as schematically shown in Fig. 1. In this example, hydrogen is produced by an electrolyser (and stored in a tank) powered by the surplus electricity from renewable energy technologies, using solar and wind (specifically at summer daytime). When RES are scarce, or demand is high, additional power is needed, so the fuel cell re-powers, using hydrogen gas, to produce electricity (usually at night and winter).

2 METHODS

The scope of this work is, first, to model a feasible configuration of a self-sufficient energy system based on RES and hydrogen technologies for a remote household located in Slovenia and, second, to experimentally validate the results of system operation. In this study, only electricity is considered. Experimentally, only hydrogen technologies are validated, while renewables are only simulated.

The HOMER[1] numerical simulation tool was used to determine optimal energy system configuration, [19]. The analysis is based on the actual geographical location, availability of energy sources, load dynamics and technical and economical characteristics of system components. An existing system with hydrogen technologies, established within Centre of

[1] http://homerenergy.com/pdf/homergettingstarted268.pdf

Excellence for Low Carbon Technologies (CO NOT), was used for experimental evaluation of the numerical results.

2.1 Energy system model and simulation

The RES-hydrogen energy system operation was determined via numerical simulation with the aid of the HOMER software tool. HOMER models an energy system's physical behaviour and its life-cycle cost, which is the total cost of installing and operating the system over its life span. It is an input/output model, making annual analyses in steps of one hour. General inputs are demands, capacities, component technical characteristics and costs. Outputs are energy balances, capacities, resulting annual production and life-cycle costs.

In this paper, the energy supply of a stand-alone household, located in Slovenia, is considered. In the model (Fig. 1), AC electrical load is supplied, via DC-AC inverter, primarily by wind turbines and photovoltaic panels. Excess electricity produced from RES is stored as electrolytically produced hydrogen. When primary RES are scarce or unavailable, the fuel cell system produces power from stored hydrogen.

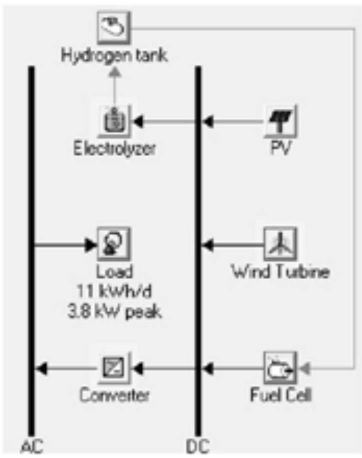

Figure 1: *HOMER numerical model of a stand-alone energy system*

2.1.1 Hourly input distributions

Actual input data time series, needed for the analysis, were obtained from real measurements. Electricity consumption data (Fig. 2) were taken from MeRegio and Mirabel projects, [20]. From among 87 consumers, a case with 11 kWh of daily power consumption was chosen. Wind and solar energy resources in Portorož, Slovenia are considered in this study. Meteorological data were acquired from ARSO's (Slovenian Environment Agency) test reference year, with annual average wind speed of 2.8 m/s, peaking at 10.6 m/s and annual average daily global horizontal radiation 3.9 kWh/m², [21]. The test reference year is historical digital data set that represents measured 365-day values of the selected meteorological variables on an hourly basis. The sequence is synthetically constructed using monthly values selected from a multiple year data set for a given location, so that the resulting test reference year is typical for the location.

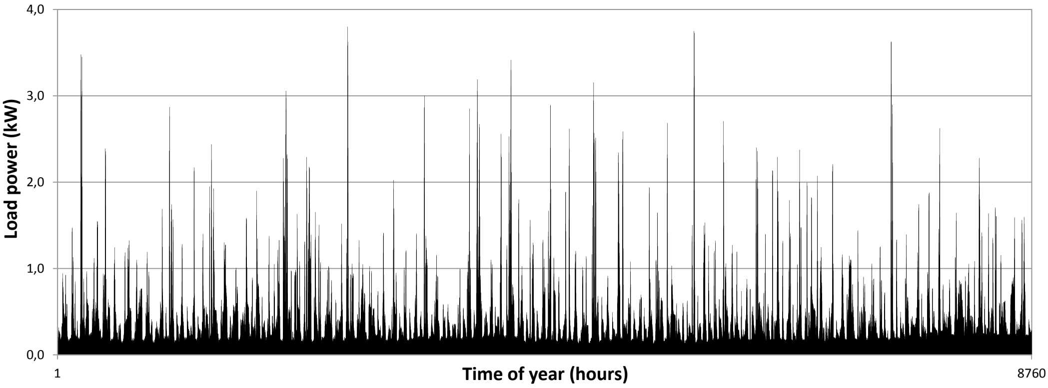

Figure 2: *Hourly electricity consumption for a one-year period*

2.1.2 Energy system components

Conversion of solar radiation to electrical energy is achieved with a photovoltaic array (PV). The power output of the PV array depends on the amount of radiation striking its surface, which is generally not horizontal. Therefore, in each time step, HOMER calculates the global solar radiation on the surface of the PV array. In the calculation of PV power output, its rated capacity, derating factor, solar radiation, temperature coefficient of power and PV cell temperature are considered, [22].

A wind turbine converts wind kinetic energy to electrical energy. Its power depends on wind speed, adjusted to hub height, and wind turbine power curve. The cut-in wind speed of the chosen wind turbine equals 3 m/s and at wind speeds 13 m/s it reaches peak output power.

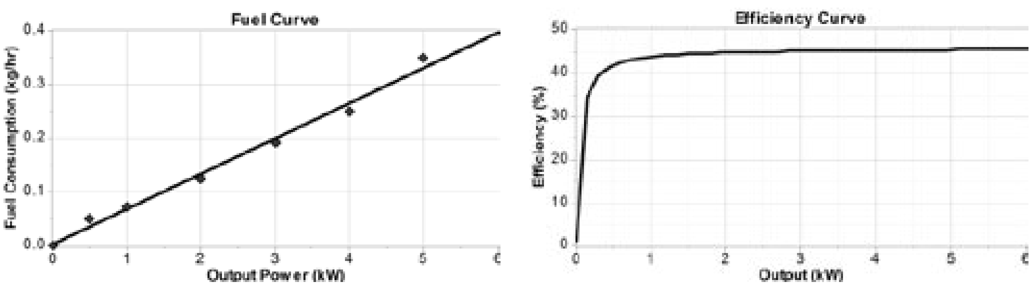

Figure 3: *Fuel cell fuel curve and efficiency, experimentally determined within CO NOT*

The hydrogen production rate is defined by electrolyser efficiency and minimum load ratio (technical minimum). Experimentally determined values, acquired within the Centre of Excellence for Low-Carbon Technologies (CO NOT), 72 and 50% respectively, were used. Hydrogen consumption is calculated using fuel curve and fuel cell electric efficiency is determined based on higher heating value, 142 MJ/kg. The hydrogen tank is a container used to store produced hydrogen for later use. The fuel cell system is used to re-power stored

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hydrogen, when there is not enough RES. The fuel cell power production depends on the fuel curve. An experimentally defined fuel curve and its corresponding efficiency are shown in Fig. 3.

2.1.3 Boundary conditions and optimisation

HOMER simulates different system configurations with several combinations of components (and their sizes) that are specified in the components inputs. All feasible system configurations are then listed in order from most cost-effective to least cost-effective, based on its net present value (NPV).

The project's lifetime is assumed to be 20 years, as well as all components' lifetime, except for the fuel cell, which has to be replaced every 20,000 operating hours. The annual real interest rate considered in the model was 6 %.

Table 1 shows component parameters as boundary conditions of the model. PV array and wind turbine sizes considered in the calculation were 10 to 30 and 5 to 20 kW, respectively. Electrolyser, fuel cell and converter sizes between 1 and 6 kW were considered. Capital costs of investment are based on invoices acquired within the project in CO NOT. Operation and maintenance (O&M) costs are based on [12].

Table 1: *Considered input component parameters*

Component	Size (kW)	Capital cost (€/kW)	O&M (% of capital cost)
PV array	10–30	1.500	0
Wind turbine	5–20	1.100	1
Electrolyser	3–6	8.000	2
Fuel cell	1–5	4.000	2,5
Power converter	4	800	0
Component	**Size (kg)**	**Capital cost (€/kg)**	**O&M (% of capital cost)**
Hydrogen tank	0–60	500	0,5

2.2 Experimental system with hydrogen technologies

An experimental system, installed at the Šoštanj thermal power plant in Šoštanj, Slovenia, was used to provide operational evaluation of hydrogen technologies in the above-described manner and calculated beforehand with simulations performed by the HOMER numerical model. The schematic of the system is shown in Fig. 4 and its photograph in Fig. 5. It is composed of alkaline electrolyser (Hydrogenics HySTAT) with 120 kW_e nominal capacity, hydrogen production rate up to 15 Nm^3/hr at 25 bar. The hydrogen tank size is 20 m^3. The PEM-type fuel cell UPS system (Future-E Jupiter) delivers 6 kW_e of power. Additional equipment consists of an electronic load (Amrel PLW) with cooling unit (Hidros LSK), measuring instrumentation (hydrogen mass flow meters, electric meters, pressure gauges, etc.), PLC (Mitsubishi Q series) and computer control system with remote access.

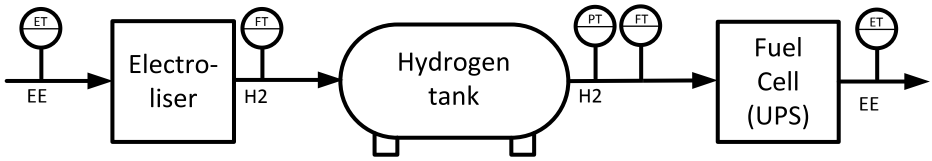

Figure 4: *General scheme of experimental system with hydrogen technologies*

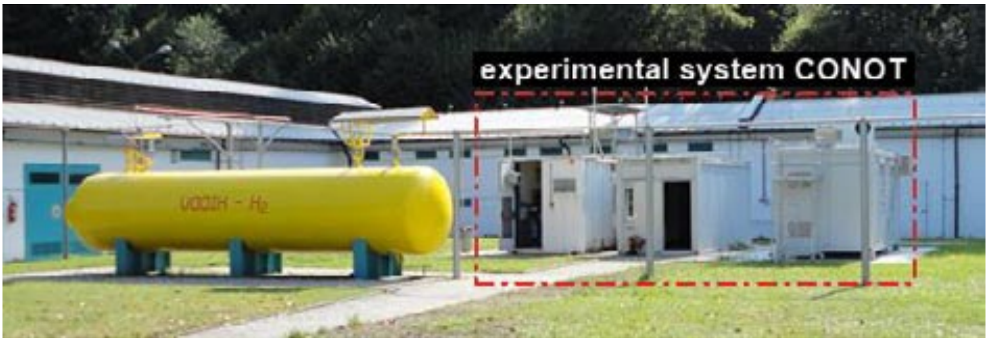

Figure 5: *Photograph of the outside of the hydrogen technology testing facilities*

3 RESULTS

3.1 Numerical simulation results

A feasible system is defined as a hybrid system configuration that is capable of meeting the load. Under given conditions, one system configuration was found feasible. It has a total of 249 different combinations of size or number of components. The optimal combination, with the lowest total net present value (€138,452), is presented in Table 2. The (levelised) cost of energy for optimal system combination is €2,901/kWh. The current electricity grid purchase price in Slovenia for households is approximately 0.15 €/kWh. Nominal primary (RES) and secondary (fuel cell) power source capacity, combined, is 34 kW, while peak demand is 3.8 kW. The optimal electrolyser and converter size is 4 kW, each, with tank capacity being 30 kg of hydrogen.

Fig. 6–Fig. 9 show major components' operating characteristics: hydrogen storage level, electrolyser power, fuel cell power and their duration curves, respectively. Hydrogen energy storage shows the ability to store inter-seasonal fluctuations in RES availability. Summers' higher RES energy density is stored to be used during colder half of the year (Fig. 6). Unlike the fuel cell (Fig. 8), the electrolyser (Fig. 7) operates during 75% of the operation time with its nominal power (Fig. 9Figure 7). In Fig. 9, the difference between electrolyser electricity consumption and fuel cell electricity production, which represents the overall efficiency of hydrogen energy storage (averaging 26%) is also shown.

Table 2: *Optimal system configuration*

Component	Size (kW)
PV array	20
Wind turbine	10
Electrolyser	4
Fuel cell	4
Power converter	4
Component	**Size (kg)**
Hydrogen tank	30

Table 3 presents an optimal system's electrical production configuration and consumption values. The PV arrays produce 80%, while the secondary power source (fuel cell) produces 9% of the electricity. The electrolyser electricity consumption rate is 69%, while the household consumes 31%. All electric load was met throughout the year, and the excess electricity is 47.5% of overall production.

Table 3: *Optimal system configuration electrical production and consumption*

Production	kWh/year	%
PV array	21,205	80
Wind turbines	3,007	11
Fuel cell	2,416	9
Total	26,629	100
Consumption	**kWh/year**	**%**
AC primary load (household)	4,161	31
Electrolyser	9,351	69
Total	13,512	100
Other	**kWh/year**	**%**
Excess electricity	12,655	47.5[a]
DC/AC conversion loss	462	11.1[b]
Unmet electric load	0	0
Capacity shortage	0	0
Renewable fraction	/	100

[a] *share of total production*

[b] *share of AC primary load*

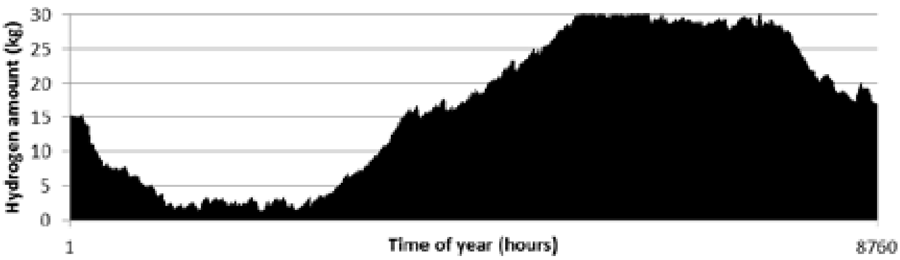

Figure 6: *Hydrogen tank storage level during the year*

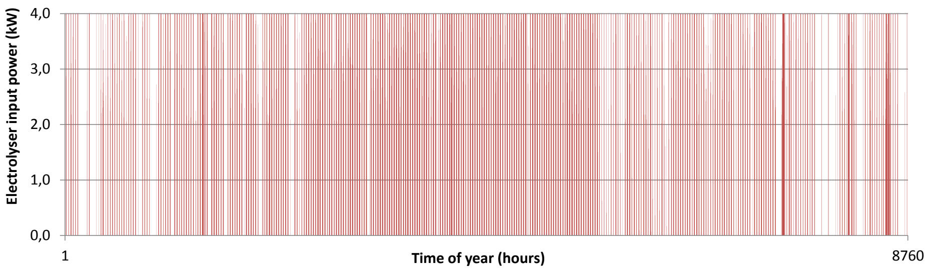

Figure 7: *Electrolyser input power: full year scale*

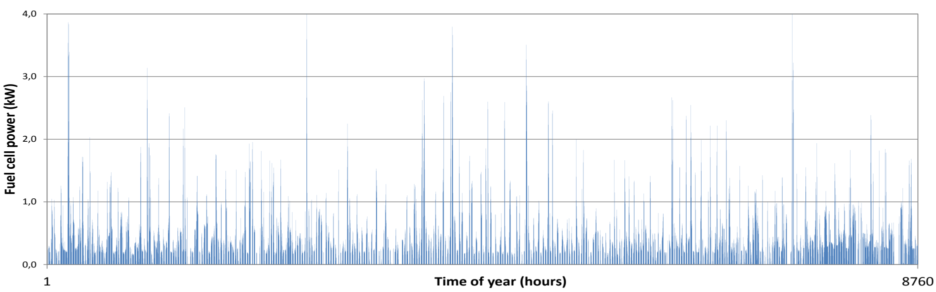

Figure 8: *Fuel cell output power: full year scale*

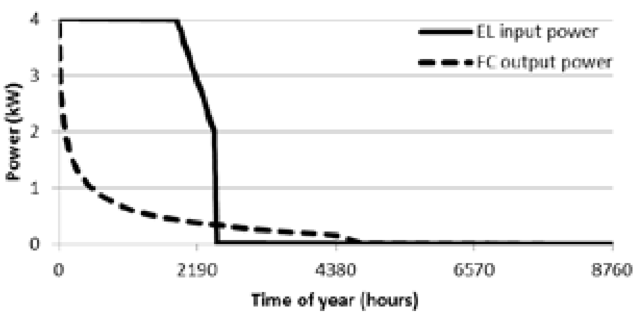

Figure 9: *Electrolyser and fuel cell duration curves*

Table 4 lists optimal system configuration characteristics, where low mean outputs and capacity factors represent its nature. Capacity factors vary from 3.4% to 12.1%, except for the electrolyser being 26.7%. Average power, from primary and secondary power sources, exceeds the average household load by 688%, the largest contribution being from photovoltaic arrays (PV) with 510% penetration. The results show similar operation time of PV and wind turbine (WT), 3,873 and 3,556 hours per year, respectively. In contrast, the electrolyser (EL) operates less frequently (2,500 hours/year) than the fuel cell (4,834 hours/year), which is also demonstrated by fewer startups. The fuel cell (FC) life span of 20,000 operating hours means that replacement is necessary after every 4.14 years. The average fuel cell electric efficiency is 42.9%.

Table 4: *Optimal system configuration characteristics*

Quantity / Component	Unit	PV	WT	FC	EL	DC/AC
Rated capacity	kW	20	10	4	4	4
Mean output	kW (kg_{H2}*)	2.4	0.34	0.5	0.07*	0.47
Minimum output	kW (kg_{H2}*)	0	0	0	0.00*	0.13
Maximum output	kW (kg_{H2}*)	17.1	9.31	4	0.07*	3.8
Capacity factor[a]	%	12.1	3.43	6.89	26.7	11.9
Component penetration[b]	%	510	72,3	105,5	/	/
Hours of operation	h/year	3,873	3,556	4,834	2,500	8,760
Full load hours	h/year	1,244	323	604	2,338	1,095
Levelised cost	€/kWh (€/kg_{H2}*)	0.123	0.355	0.79	11.50*	0.038
Number of starts	starts/year	/	/	523	395	/
Operational life	years	20	20	4.14	20	20
Fixed generation cost	€/year	/	/	0,48	/	/
Hydrogen cons./prod.	kg/year	/	/	169	171	/
Specific hydrogen cons./prod.	kg/kWh	/	/	0.07	0.018	/
Hydrogen energy input/output	kWh/year	/	/	5,627	5,694	/
Mean electric efficiency	%	/	/	42.9	72.1	90

[a] *average power output divided by the total capacity*
[b] *average power output divided by the average primary load*

3.2 Experimental results

The fact that the given experimental system configuration is unalterable prevents recreating an exact experimental match to different numerical model designs. In order to conduct an experiment in which the model and real system capacity do not match, scaling has to be applied. For the purpose of this experiment, capacity (input power), hydrogen production rate and time scaling were applied. The fuel cell system's modular design (3 × 2 kW) enabled the direct transfer of HOMER model results to be replicated in the experiment. In contrast, the electrolyser prevents any capacity adjustment; therefore, linear scaling was performed. After consulting electrolyser system operators, maximum input power in the experiment was set to 72 kW_e.

The electrolyser's experimental operation program was acquired using numerical simulation results, multiplied by 72/4. Analogue-to-input power, the hydrogen production measurements during the experiment were multiplied by 4/72. On the basis of previous experimental work conducted within CO NOT, the fast electrolyser system operation response to power changes and relatively fast start-up times (less than 10 seconds) were observed. For that reason, and due to relatively long simulation period (hourly steps in one year),the experiment's duration was limited to a period of one week in summer and scaled so that one hour in the model corresponds to one minute in the experiment. Furthermore, due to frequent start-up limitations, the electrolyser was not shut down during the experiment, but its power was reduced, as seen in Fig. 10. For the analysis, data (power and hydrogen production rate) from that period were neglected (used as zero), which is also shown in Fig. 10.

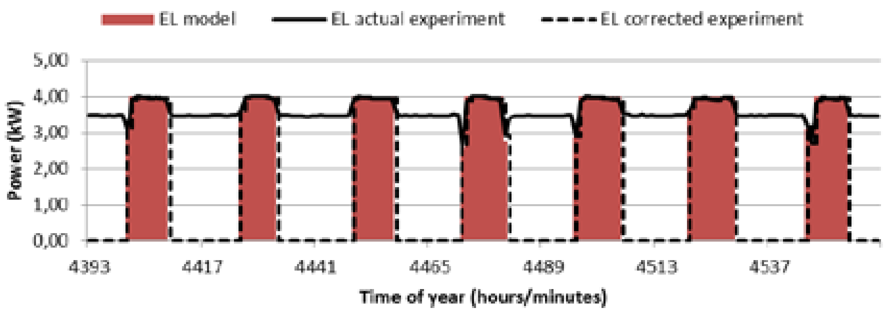

Figure 10: *Correction of experimental results by neglecting values in periods of simulated turn-off*

Fig. 11 and Fig. 12 present the chosen one-week period with both numerical and experimental results, and power and hydrogen flow rate, respectively. Fig. 12 also shows notable differences in hydrogen flow rates, which is a consequence of inaccurate or over-simplified models of both electrolysers and fuel cells in HOMER. The actual fuel cell UPS system also contains a battery, and the electrolyser contains an internal pressure buffer and hydrogen filtering discharge etc.

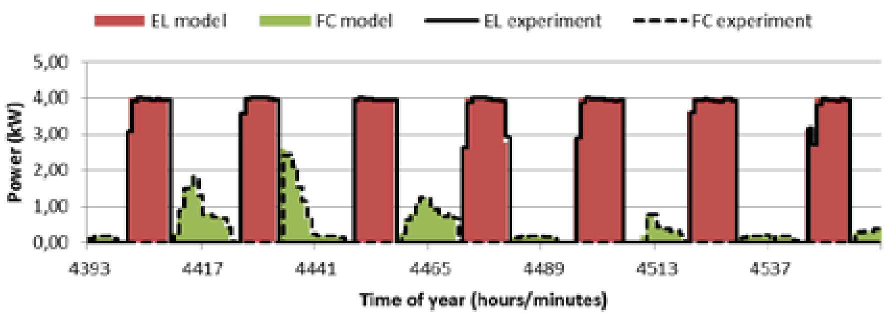

Figure 11: *Simulation and experimental power distribution of 1-week period in summer*

A comparison of integral parameters, both simulation and experiment, presented in Table 5, shows remarkably good matches of both results, with differences of less than 3%.

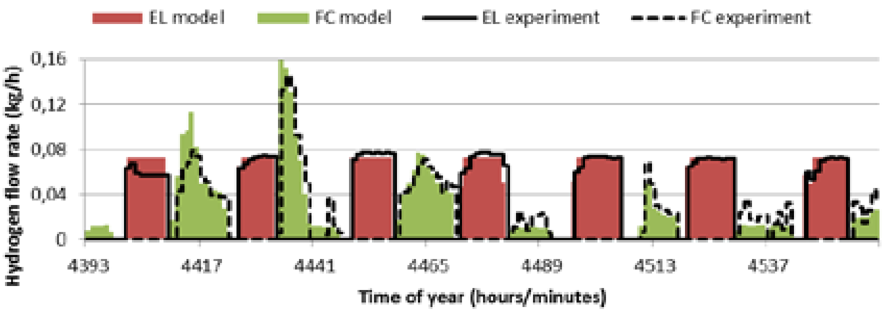

Figure 12: *Simulation and experimental hydrogen flow rate distribution of 1-week period in summer*

Table 5: *Simulation and experiment results comparison*

Parameter	Unit	EL model	EL experiment	Index	FC model	FC experiment	Index
energy	kWh	4.204	4.172	0.99	0.742	0.721	0.97
H2 amount	kg	0.077	0.075	0.97	0.046	0.045	0.98
el. efficiency	%	72.2%	70.9%	0.98	40.9%	40.6%	0.99

4 DISCUSSION

In this paper, a numerical model of an RES-hydrogen energy system was experimentally validated with a mere 3% difference in results. The proposed method was proven suitable for the system planning and design of hybrid energy. Therefore, sustainable and renewable energy supply of a stand-alone household in Portorož is technologically feasible with the use of 100% RES in a combination with hydrogen technologies, although costly due to large and expensive RES capacities. The turnover point is at an electricity grid purchase price increase of over 200% (from €0.15 to 0.45 /kWh) and the simultaneous decrease of RES technology costs by up to 80% and an increase in its efficiency.

The discussed energy system requires large production capacity, which results in considerable excess electricity production (almost 50%) and low energy utilisation (low capacity factor). Due to low resource availability and intermittent seasonal energy, large capacity storage is required. However, the ability to store hydrogen between seasons is uncommon in comparison to most other storage technologies and in this regard presents its advantage. The weakness of hydrogen storage is best indicated by its low overall energy efficiency of 26%. Potential technical development could, however, increase storage efficiency to approximately 50%.

Currently available and the most common hydrogen technology (PEM fuel cell UPS and alkaline electrolyser) has been shown to be fairly suitable for considered dynamic power balancing

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operation with fluctuating renewables. The UPS system successfully meets the simulation requirements for fast start ups and power ramping, while electrolyser simulation shows that it mostly operates at constant load; therefore, only its fast startups are required. Considering minor changes in current alkaline electrolyser system design (e.g. uniform cooling system installation in series with fuel cell for cool down prevention and shutdown hydrogen depressurisation disabling) hydrogen production could be started quickly, within minutes. Hydrogen technology's dynamic operation for balancing power supply and demand requires frequent startups and shutdowns (approximately 1.5 times per day) which negatively affects the equipment's lifespan. It must also be noted that single household consumption is the most extreme case in terms of power fluctuation and supplying aggregated consumers (several household or community) would decrease the relative system operation dynamics.

Scaling results, of a fuel cell or electrolyser, linearly, raises a question of accuracy. Some error in results and reduced relevance could rightly be recognized. Arguments in favour of this method (linear scaling) are the fact that (a) fuel cells (and electrolysers, since it is essentially the same process) are unique as energy converters, i.e. their range of application (in terms of power and use) far exceeds all other types [23], (b) most auxiliary power is used for cooling which is proportional to power, (c) one large unit in the model can in reality be substituted by several smaller ones (dispersed or centralised), and (d) EL and FC are both in essence already composed of multiple individual cells (forming stack), implying their fundamental ability to scale.

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APPLICATION AND TESTING OF STEELS FOR THE ENERGY PROCESS INDUSTRY

UPORABA IN PREIZKUŠANJE JEKEL ZA ENERGETSKO PROCESNO INDUSTRIJO

Zdravko Praunseis[ℜ], Jurij Avsec, Renato Strojko, Sonja Novak

Keywords: energy steels, process industry, fracture CTOD tests

Abstract

The aim of this paper is to analyse the fracture behaviour of high-strength low-alloyed steels for application in the energy process industry, and also to determine the relevant parameters that contribute to higher critical values of fracture toughness. For all testing of the steel specimens, fatigue pre-cracking was carried out using the GKSS Step-Wise High R ratio method (SHR) procedure. During the Crack Tip Opening Displacement (CTOD), the DC potential drop technique was used for monitoring the stable crack growth. The load line displacement (LLD) was also measured with a reference bar to minimize the effects of possible indentations of the rollers. The CTOD values were calculated in accordance with the BS 5762 standard and also directly measured via the GKSS-developed δ_5 clip gauge on the specimen side surfaces at a fatigue crack tip-over gauge length of 5 mm.

Povzetek

Namen članka je analiza lomnega obnašanja modernih visokotrdnostnih drobno zrnatih jekel za uporabo v energetski procesni industriji in določitev relavantnega parametra za merjenje izmerjenih vrednosti lomne žilavosti. V vse jeklene preizkušance je predhodno nameščena utrujenostna razpoka izdelana po metodi SHR, ki je bila razvita v centru GKSS. Med merjenjem vrednosti konice odpiranja razpoke (CTOD) je uporabljena metoda padca potenciala (DC) za

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določitev stabilne rasti razpoke. Izmerjen je tudi pomik v smeri sile (LLD) s posebno merilno naprava, ki zazna pomike podpornih valjčkov med preizkušanjem. Odpiranje konice razpoke (CTOD) je izračunano po angleškem standardu BS 5762 in neposredno izmerjeno z metodo GKSS, ki uporablja posebno merilno napravo montirano na konico utrujenostne razpoke z začetnim razmikom 5mm.

1 INTRODUCTION

With High-Strength Low-Alloyed Steels (HSLA) and their welded joints, the thermal and strain cycles during welding inevitably bring about metallurgical, mechanical and other heterogeneities. Fig. 1 and Fig. 2 show a summarised illustration of effects of various characteristics on fracture joint performance and/or fracture transition behaviors. Almost all of these factors result in the deterioration of the fracture performance of welded joints, [1,8].

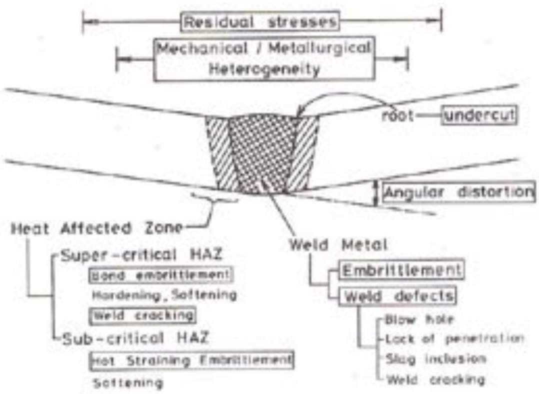

***Figure 1:** Mechanical characteristics of energy steel welds*

Microstructures in welded joints of structural steels can be roughly divided as follows with regard to the change of material characteristics: (1) welded metal, (2) fusion line, (3) supercritical HAZ, and (4) subcritical HAZ. There are two main controlling factors that dominate the fracture performance of welded joint: factors controlling (a) fracture toughness and (b) deformation behavior under loading. Although the fracture performance of welds is affected by various factors and their complex combined incidence, the following two controlling factors of brittle fracture strength of welds are essential: (I) the embrittlement in HAZ and the weld metal in the vicinity of pre-existing defects, and (II) inhomogeneity in strength, such as hardening and softening in HAZ and matching between the weld metal and base metal. The various factors control the embrittlement in welds. Mechanical heterogeneity is also a result of the same kind of controlling factors, [6,7]. In particular, as mentioned above, the embrittlement results in problems with the existence of local brittle zones (LBZs) in multi-pass welds.

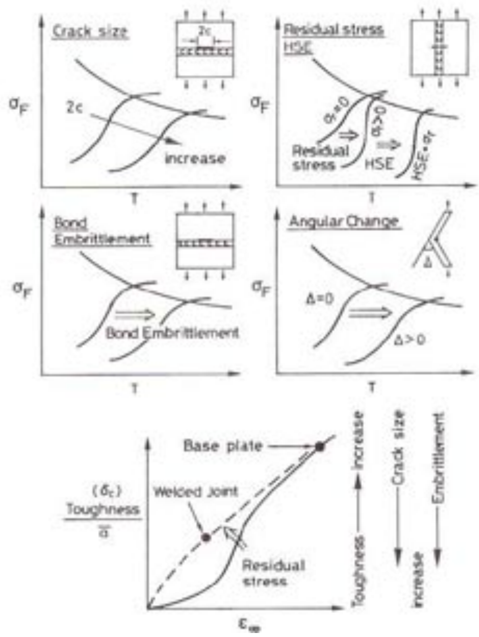

Figure 2: *Summary of various controlling factors on fracture performance of energy steel welds.*

2 EXPERIMENTAL PROCEDURE

The crack tip opening displacement (CTOD) test was developed in the U.K. during the 1960s. The first draft for the methods for CTOD testing were prepared as British Standard DD19 (1972). The CTOD test specimen (Fig. 3) contained a fatigue-pre-cracked notch and was loaded in a three-point bending to fracture.

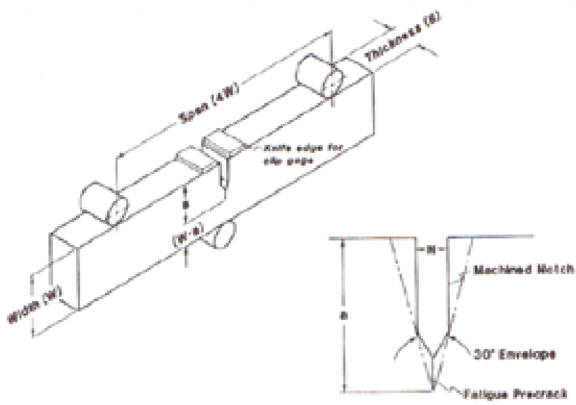

Figure 3: *Three-point bending CTOD test specimen.*

The critical CTOD was obtained via the clip-gauge displacement *Vg* measured across the notch mouth by using a certain converting equation. In 1979, the above testing method was specified as BS 5762 [2]: British Standard Methods for Crack Opening Displacement (COD) Testing (1979). In the current British Standard, the CTOD be calculated from the new equation as follows:

$$\delta = \frac{K^2}{2\sigma_Y E'} + \frac{0.4(W-a)\,V_p}{0.4W + 0.6a + z} \tag{2.1}$$

where the first term is the elastic component of CTOD, the second term is the plastic component, and *Vp* is the plastic component of the clip-gauge displacement. The stress intensity factor for the elastic CTOD calculation is obtained from the following relationship.

$$K = YP / BW^{1/2} \tag{2.2}$$

where *P* is the applied load, and *Y* is the stress intensity coefficient given as a function of the crack length-to-width ratio.

In this standard, the type of critical CTOD was clearly defined according to the nature of the observed fracture event. The four kinds critical CTOD, i.e. δ_c, δ_u, δ_m and δ_i, are measured (Fig. 4). At low temperatures, the steel fails by cleavage and δ_c is measured empirically.

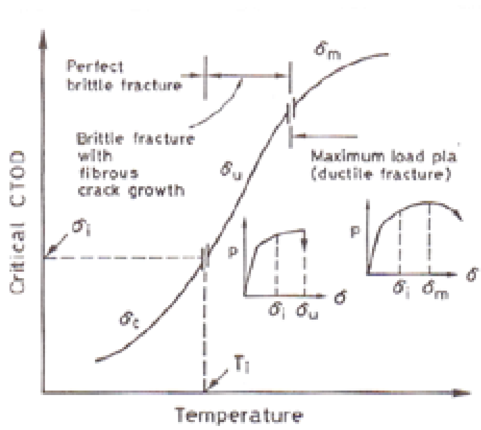

Figure 4: *Definition of critical CTODs in BS 5762.*

As the test temperature increases, cleavage becomes less favorable and the fracture toughness increases. The fracture mode changes to microvoid coalescence, and the crack grows in a stable manner. δ_i is defined as the value of CTOD at the onset of tearing. At temperatures slightly above the fracture mode change, stable tearing can be followed by unstable cleavage. In this case, the critical measure is δ_u at the instability point. On the upper level of toughness, the steel reaches a point of plastic collapse when the work-hardening cannot keep pace with the decrease in ligament area caused by stable crack growth. δ_m is then measured at the point of maximum load in a bend test.

The fracture toughness of heterogeneous regions of HSLA steels was evaluated using a standard static Crack Tip Opening Displacement (CTOD) test at the Geesthacht Research Center [5]. All

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CTOD tests were conducted using Zwick (20t) and Schenk (100t) testing machines. Specimen loading was carried out with constant crosshead speed v = 0.5 mm/min. The test temperature was -10°C, following the recommendation of the OMAE (Offshore Mechanics and Artic Engineering) association. For CTOD testing, the single specimen method was used. To evaluate the fracture toughness of under-matched welded joints, standard bending specimens, [2-4] with deep (a/W = 0.5) and shallow (a/W = 0.25 - 0.4) notches in the weld metal and HAZ were used, [1,6,7]. For all specimens, fatigue pre-cracking was carried out with the Step-Wise High R ratio method (SHR) procedure, [5]. During the CTOD tests, the potential drop technique was used for monitoring stable crack growth, [1]. The load line displacement (LLD) was also measured with a reference bar to minimise the effects of possible indentations of the rollers. The CTOD values were calculated in accordance with BS 5762, [2], and also directly measured using a clip gauge on the specimen side surfaces at the fatigue crack tip over a gauge length of 5 mm, [5].

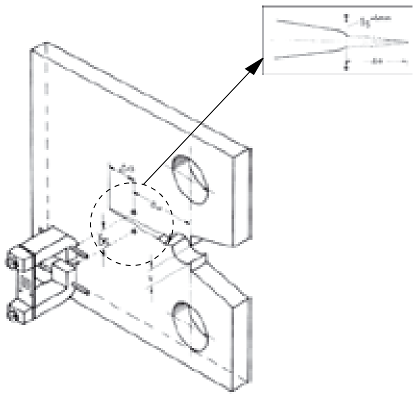

Figure 5: *Direct measurement of CTOD values at crack tip of fracture mechanics specimen*

For fracture mechanics, standards for the treatment of welded joints suitable are not yet available, but different procedures exist, [1, 6-8], recommending different ways of fatigue crack positioning in weld joints. Different positions and depths (a/W) of fatigue cracks in welds were chosen, taking this into account.

3 RESULTS AND DISCUSSION

The basic values of the yield strength and tensile strength of the tested steels were obtained from engineering stress (R) - strain (e) diagrams. It is known that engineering material curves cannot be used for the analysis of material deformation characteristics or for finite element calculations in the range of high plastic deformations.

For this purpose, the true stress-strain curve (Fig. 6) was used, which is described by the power law expression, [1]:

$$\sigma = \sigma_0 e^n \tag{3.1}$$

where σ_0 is the fictitious yield strength and n is the strain-hardening exponent.

$$n = \frac{\log \frac{R_m(1+A_{gt})}{R_{p0,2}}}{\log \frac{\ln(1+A_{gt})}{e_{0,2}}} \tag{3.2}$$

where R_m is the ultimate tensile strength, A_{gt} is the engineering extension at the maximum tensile load, $R_{p0,2}$ is the yield strength equivalent to 0.2 percent of proof stress and $e_{0,2}$ is the engineering extension.

$$e_{0,2} = \frac{R_{p0,2}}{E} + 0,002 \tag{3.3}$$

where: E is Young's module.

Finally, the fictitious yield strength σ_0 was calculated by:

$$\sigma_0 = R_{p0,2} 10^{\frac{n}{n-1}\log\frac{E_{e0,2}}{R_{p0,2}}} \tag{3.4}$$

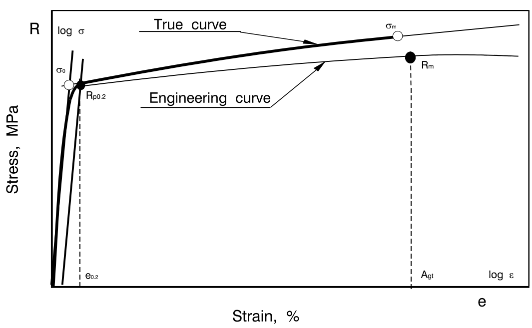

Figure 6: *Engineering and true stress - strain curves for uniaxial tension*

During CTOD testing of fracture mechanics samples, the appearance of pop-ins at the propagating crack tip was expected. These moments are detected by force-displacement relationship (Fig. 7), which are evaluated according to the standard, [4], depending on their size (decrease of force and sudden increase of displacement). The maximal CTOD toughness was measured in the samples with the crack tip.

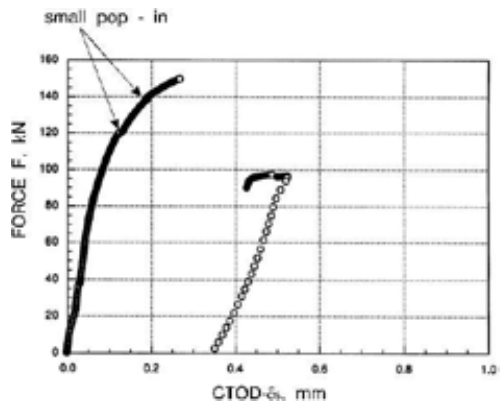

Figure 7: *Appearance of local brittle zones during CTOD testing and final fracture of fracture mechanics specimen*

The basic aim of the fractographical investigation was to determine the location of brittle fracture initiation on the fracture surface of CTOD test samples and to identify the brittle fracture initiation point by using Energy Disperse X-ray (EDX) analysis. Microstructures at the brittle fracture initiation point and around it, as well as crack path deviation nature, were evaluated using the fracture surface cross-section method [1,8] through the brittle fracture initiation point. A detailed analysis of material at the crack tip region and along deviated crack path was made with an optical microscope and scanning electron microscope. In this way, the critical microstructure (local brittle zones) at the fatigue crack tip surroundings, where the brittle fracture was initiated, and the microstructure, where it propagated later, were identified. For fractographical and metallographical analysis, the most representative fractures of CTOD test samples were chosen, which also appeared in other samples in appropriate shapes.

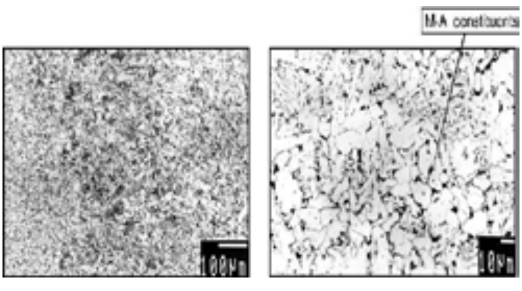

Figure 8: *Ferritic microstructure with distributed brittle M-A constituents along ferrite grain boundaries*

In the case of CTOD testing of specimens with the crack tip located in the thickness direction, the lowest CTOD test value was measured due to the appearance of the first brittle fracture in the mainly ferritic microstructure with carbides (Fe_3C), precipitated at the grain boundary (Fig. 8, Fig. 9 and Fig. 11) and appearance of brittle fracture initiation point, i.e. Al-Si-Mn inclusions (Fig. 10).

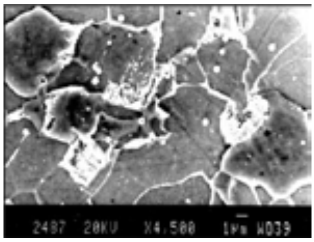

Figure 9: *Mainly ferritic microstructure with carbides (Fe_3C) precipitated at the grain boundary*

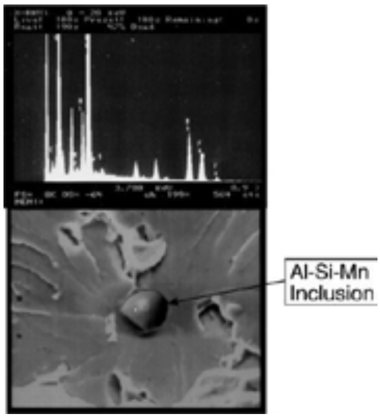

Figure 10: *Appearance and EDX analysis of brittle fracture initiation point, i.e. Al-Si-Mn inclusion*

It should be noticed that for correct identification of the brittle fracture initiation point, it is of the utmost importance to apply EDX analysis to both fracture surfaces. Otherwise, it could happen that the EDX analysis mistakenly detects a false brittle fracture initiation point.

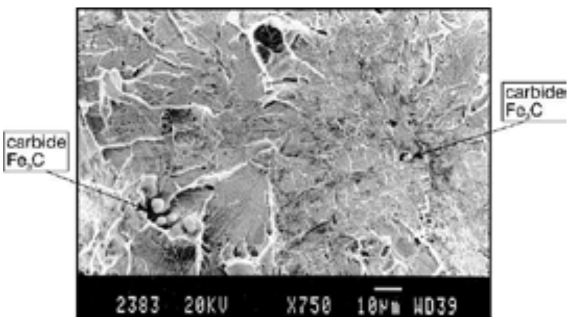

Figure 11: *Identification of brittle fracture initiation point as Fe_3C on the fracture surface of CTOD test sample*

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4 CONCLUSIONS

1. In the heterogeneous regions of HSLA steel welded joints, microstructures change from that of the base metals because of the weld thermal/strain cycles. This change brings about the variation of mechanical properties such as yield strength, ultimate tensile strength, strain hardenability and elongation; in particular, they take place even in the macroscopic scale.

2. It can be understood from the basic experiments that fracture initiation in materials with a local brittle zone in the vicinity of crack tip is controlled by the fracture toughness of the embrittled region, and that the size of the local brittle zones along the crack front play a decisive role in the scatter of fracture toughness.

3. The brittle fracture initiation points of welds were indicated as a Mn-Al-Si inclusion or TiCN carbide (according to EDX analysis), and are found just below the blunting line, which is in agreement with the brittle fracture model theory. It should be noted that for correct identification of a brittle fracture initiation point it is of utmost importance to apply EDX analysis to both fracture surfaces. Otherwise, it could happen that the EDX analysis mistakenly detects a false brittle fracture initiation point.

4. Good agreement between calculated (δ_{BS}) and measured (δ_5) CTOD values is obvious from the comparison of CTOD values, verifying the method of direct measurement of CTOD, for which the material property data (e.g. yield strength) is not necessary, in contrast to the calculated CTOD values according to the BS 5762 standard. This argument favours using direct measurement δ_5 at the crack tip in welded joints with local and global strength mismatching, and precludes the application of the BS 5762 standard for welded joints, which is valid for the base material.

Acknowledgements

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MODELLING CONFLICT DYNAMICS IN AN ENERGY SUPPLY SYSTEM

MODELIRANJE DINAMIČNIH KONFLIKTOV V ENERGETSKEM SISTEMU

Janez Usenik[ℜ], Tit Turnšek

Keywords: conflict, generic model, social interaction, stock-and flow diagram, system dynamics, fuzzy inference system

Abstract

This paper presents a model of conflict, the precise definition of which is also presented in this paper. The system dynamics paradigm is often used to model the dynamics of social interactions. The basic ideas leading to conflict models in form of difference, i.e. differential equations, and finally to an expanded model with fuzzy logic inference are presented.

Tremendous progress in this field has been made by two groups of researchers. Gottman et al., [1], modelled marital interactions and set up a model in the form of differential equations. Coleman in his group, [2], established the model of group interaction in the form of differential equations. There are many types of social interactions; conflict is merely one of them. We define conflict as a destructive, dysfunctional interaction between actors. According to this view, we developed a conflict model, arising from the model of Coleman et al., first in the form of differential equations and then in the form of a stock-and-flow diagram, according to paradigm of system dynamics. We attempted to keep the results of the model understandable for a broad range of managers and officials at different levels within the energy sector. At the end, a numerical example is given.

Povzetek

V članku je predstavljen dinamični model konflikta. Dinamiko odnosov in relacij v modelu za zvezne sisteme opišemo z uporabo diferencialnih enačb. v nadaljevanju razvoja teorije pa model

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nadgradimo še z uporabo mehke logike. Velik napredek na tem področju sta opravili dve ločeni raziskovalni skupini. Gottman, Murray in ostali, [1], so se ukvarjali z odnosi med zakoncema, kar so modelirali s sistemom diferenčnih enačb. Skupina raziskovalcev pod vodstvom Colemana, [2], pa je razvila model v obliki diferencialnih enačb. Obstaja mnogo vrst družbenih interakcij, konflikti so le ena od njih. V članku izhajamo iz definicije, ki opredeljuje konflikt kot destruktivno neuglašeno zvezo med dvema akterjema. Glede na to definicijo postavimo model konflikta v skladu s Colemanovim pristopom najprej v obliki sistema diferencialnih enačb, ki ga rešujemo s pomočjo grafičnega pristopa sistemske dinamike. Rezultate lahko uporabimo na širokem področju upravljanja sistemov. Vsi izsledki, relacije in rezultati veljajo tudi za področje upravljanja energetskega sistema. Na koncu članka je dodan numerični primer, ki ilustrira teoretično podlago modela.

1 INTRODUCTION

Different conflicts can be observed in the energy sector at any level of society, from individual, organizational, intra-state, to the international level. There are conflicts about the use of energy resources, building power plants and investment priorities. There are opposing interests between legislators, producers and consumers that lead to conflicts. Ecologists oppose nearly every interference in the environment. Local communities often oppose transmission lines, as the storage and transportation of nuclear waste etc. Many international conflict occur around the crude oil, gas resources and pipelines.

Some conflicts will be settled without any outside intervention; others will escalate to a certain level and remain stabilised at that level, and there are also conflicts that will oscillate.

Do we really understand the mechanisms driving conflict dynamic? What do all these conflicts have in common?

We see conflict as a specific malignant kind of social interaction, usually between two parties (actors). Conflict is something that should be settled and reconciled. Not all scholars share this opinion; some see conflict as driving force of progress. If we would like to affect full reconciliation, it is useful to understand conflict dynamics. This paper takes a closer look into the internal workings of conflict dynamics.

2 MODELLING CONFLICT DYNAMICS – OVERVIEW

Studies of conflict dynamics are mostly based on the theoretical works of Deutsch, [3, 4], Richardson, [5], Pruitt [6-9], and Coleman [10].

Coleman characterized an intractable conflict as ‘one that is recalcitrant, intense, deadlocked, and extremely difficult to resolve’, [10]. Deutsch explained this with his so-called crude law of social relations: ‘The characteristic processes and effects elicited by a given type of social relationship (cooperative or competitive) also tend to elicit that type of social relationship’, [11]. The concepts of conflict dynamics in the context of cooperation and competition as developed by Deutsch, [10], drive the conflict into one of the stable states, i.e. the attractors, [2, 12]. Many conflicts are settled before they escalate. It must be noted that not every divergence can be characterized as conflict. However, if a conflict develops in a destructive direction and is not settled on time it will most probably escalate accompanied by series of incremental

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transformations, [9]. The narrow, but consistent, and stable structure of emotions, perceptions, beliefs, feelings, values, thinking, behaviours and communication arise. Once structural changes are strengthened, they become difficult to eliminate, and conflict become intractable. As we will see later, a conflict can reach a certain stable state, known as the 'attractor', and conflict dynamics maintain this stable state. Nothing can grow endlessly, and the psychological states of actors will reach a stable or unstable equilibrium. The conflict spiral will go forwarded but conflict will no longer escalate, [9].

Two groups of researchers, Gottman-Murray et al. (Gottman, Murray, Tayson, Swanson and Swanson) and Coleman et al. (Coleman, Vallacher, Nowak, Liebovitch, Bui-Wrzosinska), have significantly contributes to understanding conflict dynamics.

3 THE MODEL OF GOTTMAN ET AL.

Gottman et al. developed a formal mathematical model of marital conflicts as the theory [1, 13]. The emotional state (behaviour) of wife to her husband is denoted W_t, and emotional state (behaviour) of husband to his wife is denoted H_t ($t=1,2,3,....$). W_t and H_t can be positive or negative. The rates of change of emotional states are determined by two components: the influenced component and the uninfluenced component. The uninfluenced component reflects the behaviour of one partner, when she or he is not influenced by other partner. Gottman et al. formulated the influence of the husband behaviour on his wife, respectively the wife's behaviour on her husband with influence functions denoted as $I_{HW}(H_t)$, and $I_{WH}(W_t)$. A complete model with influence functions is presented by the difference equations

$$W_{t+1} = I_{HW}(H_t) + r_1 W_t + a \tag{3.1}$$

$$H_{t+1} = I_{WH}(W_{t+1}) + r_2 H_t + b \tag{3.2}$$

$$t = 0, 1, 2, ...$$

where the constants *a* or *b* reflects the essence of nature of each person, and the constants r_1 or r_2 determine how quickly the person will return to its set point when it is uninfluenced. The constants r_1 and r_2 are known as the inertia to change. Only values of $|r_i| < 1$, $i=1, 2$ are meaningful, because only in this case will the system move towards its steady state.

The model was improved and expanded Gottman et al., [1].

4 THE MODEL OF COLEMAN ET AL.

Coleman, Vallacher, Nowak, Liebovitch, Bui-Wrzosinska developed mathematical model of conflict between two actors in the form of two nonlinear ordinary differential equations (Liebovitch, et al., 2008).

$$\frac{dx}{dt} = m_1 x + b_1 + c_1 \cdot tgh\, y \tag{4.1}$$

$$\frac{dy}{dt}=m_2 y+b_2+c_2\cdot tgh\,x \tag{4.2}$$

where $x(t)$ and $y(t)$, $t\in[0,T]$,$T<\infty$ represent the emotional state of each actor, and can be positive or negative. Both of these influence functions are presented as hyperbolic tangent functions. The terms m_1x and m_2y represent the inertia to change and constants b_1 and b_2 drive the uninfluenced changes. Colman et al. analysed three different interactions between actors: positive feedback between both groups ($c_1>0$, $c_2>0$), negative feedback between groups ($c_1<0$, $c_2<0$) and positive feedback from one group and negative feedback from the other group ($c_1>0$, $c_2<0$), [14].

5 MODEL OF ISOLATED CONFLICT

Formal modelling of conflict requires a rigorous definition of this phenomenon. There are many definitions that emphasize different aspects and/or types of conflict. According to our understanding, we developed the following working definition of conflict: conflict is always a destructive, dysfunctional social interaction between actors that is characterised by a perception of incompatibility of goals, interests, values, beliefs, preferences etc., which is mirrored in the hostile emotional states of the actors. The gravity of conflict can be measured as the levels of emotional states of actors. We stick to the traditional view of conflict, which considers the conflict as something negative, which is connected with quarrelling, psychopathology, social unrest, etc., In all cases, conflict is disturbance, which has to be reconciled or abolished, [15]. We will limited our discussion (and modelling) to conflicts between two actors, i.e. to dyadic conflicts.

5.1 The model

Our proposed model of isolated conflict arises out of the Coleman model of Equations (4.1), (4.2). We have modified this according to our definition of conflict. The values of both of the variables presenting (hostile) emotional states of both of the actors can only be positive or zero. Conflict exists or it does not exist; it might be stable or it might escalate, de-escalate or oscillate. This means the $x(t)\geq 0$ and $y(t)\geq 0$ for all $t\in[0,T]$. One of the reasons for this is our intention to include interactions between conflict and its environment later on. Reactions of the environment to conflict are entirely different from reactions to cooperation. The model of isolated conflict should be easy to widen with fuzzy logic inference. In this context, the differential equations modelling conflict have meaning only in the first quadrant. The influence functions remain S-shaped. We shifted the hyperbolic tangent functions into the first quadrant, and modified them. We used the following form of influence functions:

$$f_1(y)=\frac{tgh\left(\frac{y}{g}-h\right)+1}{2} \tag{5.1}$$

$$f_2(x)=\frac{tgh\left(\frac{x}{g}-h\right)+1}{2} \tag{5.2}$$

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where parameter *g* accommodates the slope of both of the functions, and extends them, parameter *h* determines the shit of hyperbolic tangent to right. The value of *h* is chosen so that the values of functions (5.1) and (5.2) for $x=0$ and $y=0$, respectively, are close enough to zero. The proposed model is given by two differential equations:

$$\frac{dx}{dt}=m_1x+b_1+c_1\frac{tgh\left(\frac{y}{g}-h\right)+1}{2} \tag{5.3}$$

$$\frac{dy}{dt}=m_2y+b_2+c_2\frac{tgh\left(\frac{x}{g}-h\right)+1}{2} \tag{5.4}$$

Parameters m_1 and m_2 ($m_1<0, m_2<0$) reflect the resistance against the conflict. In our model, this resistance should grow in proportion with emotional state; it is the result of many factors, such as costs of conflict, limitation of resources, and also ethical norms and values. For international or ethnical conflicts, public opinion play an important role. The terms $m_1.x$ and m_2y are limiting to the growth of the conflict. The constants b_1, b_2, m_1 and m_2 determine the uninfluenced set points, and the rates of change in the emotional states without outer influences. Constants b_1 and b_2 can be positive or negative. A positive value means that without the influence of another actor, the emotional level will become increasing hostile against the other actor until a set point is reached. The constants present the basic attitude of one actor against the other actor. This also means that conflict is unavoidable. Negative values of constants b_1 and b_2 will drive the emotional level in opposite direction, towards zero.

Our major concern is the behaviour of model. What drives the conflict? How do different values of parameters influence its behaviour? What kind of behaviour can we expect? Where are the critical points, and are they stable?

There are few methods to answer such kinds of questions. We can use the phase plane (*x-y*), to present the whole family of solutions. This is a very useful qualitative method for analysing the system of a differential equations, [16].

Another possibility to solve and analyse these differential equations is to use Laplace or z-transformation, and map in to complex plane, [17, 18]. In this case, we have to use piecewise linear function on a finite interval $a \le t \le b$ where the function is defined, instead of the tangent function. This will change the conditions of conflict, so we decided to take another approach.

When the models are more sophisticated, when they include fuzzy variables and fuzzy logic inference, then they cannot be formulated as a system of differential equation, and we need other tools to model and analyse conflicts. The system dynamics paradigm, and stock-and-flow modelling is a convenient alternative.

5.1.1 Stock-and-Flow model of conflict

We translate the system of differential equations (5.3) and (5.4) into a so-called stock-and-flow model. The model can be simulated on the computer, and its behaviour can be observed in detail. We used the stock-and flow-modelling methodology, based on system dynamics paradigm as defined by Forester, [19, 20], and Bossel, [21], and further developed at the Massachusetts Institute of Technology. This modelling methodology is widely used in different

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fields, such as mathematical biology, management, social science, physics, chemistry, and environmental sciences. At present, there are a few software packages that implement system dynamics modelling, the most popular of which are Vensim, STELLA and iThink. We used the Vensim PLE. The model is shown in Figure 1.

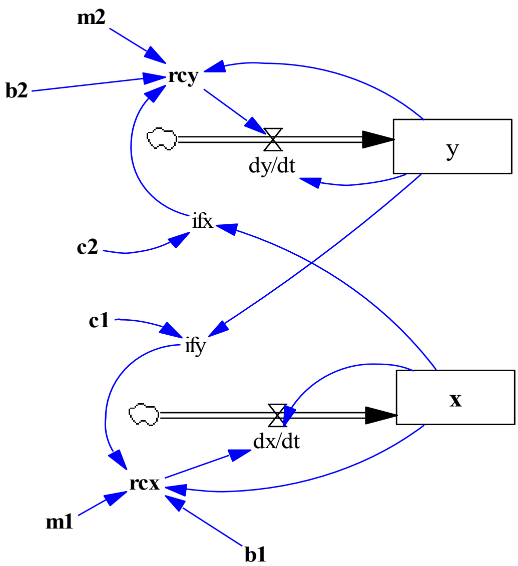

***Figure 1:** Stock-and-Flow model*

6 SIMULATION RESULTS

We can run the model with different values of parameters, and different initial value $x(0), y(0)$. We will see four different types of behaviour:

1. The model has one stable point, which is high. The emotional levels $x(t)$ and $y(t)$ go asymptotically to the stable point, independently of the initial values $x(0), y(0)$ (See Figure 2)
2. The model has two stable points, one high and one low. The emotional levels $x(t)$ and $y(t)$ go asymptotically to the higher or to the lower stable point, depends on the initial values $x(0), y(0)$ (Figures 3 and 4)
3. If the lower stable state is negative (in the third quadrant), and initial values $x(0), y(0)$ are below a threshold value, $x(t)$ and $y(t)$ will de-escalate toward the lower stable, point which is negative. When they achieve value zero at a time t_{zero}, the conflict is over, and $x(t)=0, y(t)=0$ for $t \geq t_{zero}$ (Figure 5).
4. The model has one stable point, which is low. The emotional levels $x(t)$ and $y(t)$ go asymptotically to the stable state, independently of the initial values $x(0), y(0)$ (Figure 6)

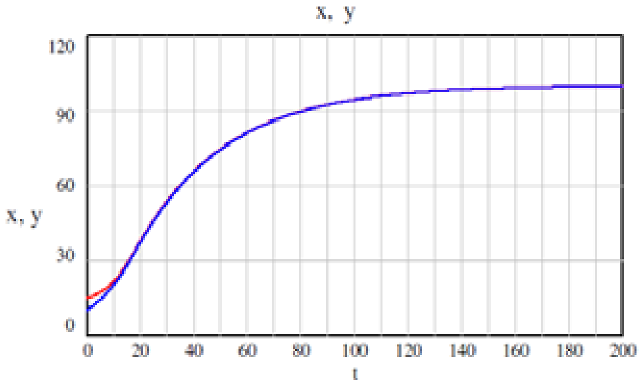

Figure 2: *Emotional levels. Parameters: m_1=m_2=-0.03; c_1=c_2=2.5; b_1=b_2=0.5. Initial values x(0)=10, y(0)=15*

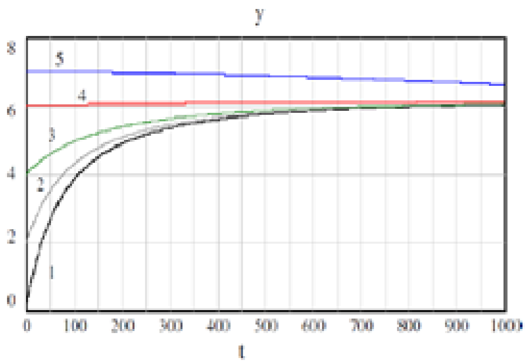

Figure 3: *Emotional level y(t). Parameters: m_1=m_2=-0.03; c_1=c_2=2.5; b_1=b_2=0.037. Initial values: x(0)=y(0)= 1:(0.1, 0.1), 2:(2, 2), 3:(4, 4), 4:(6, 6), 5:(7, 7)*

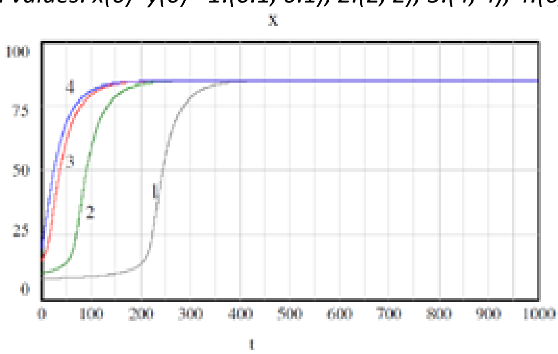

Figure 4: *Emotional level y(t). Parameters: m_1=m_2=-0.03; c_1=c_2=2.5; b_1=b_2=0.037. Initial values: x(0)=y(0)=1:(8, 8), 2:(10, 190), 3:(15, 15), 4:(20, 20)*

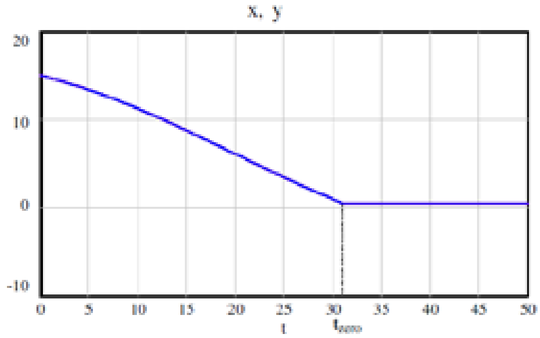

Figure 5: *Emotional levels. Parameters: m_1=m_2=-0.03; c_1=c_2=2.5; b_1=b_2=-0.5. Initial values: x(0), y(0)= 15*

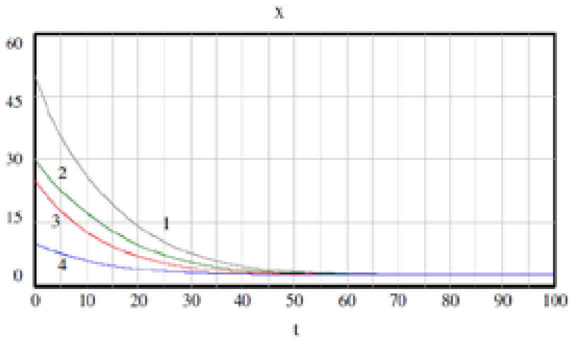

Figure 6*: Emotional levels x(t). Parameters: m_1=m_2=-0.09; c_1=c_2=0.75; b_1=b_2=0.2. Initial values:(x(0), y(0)= 1: (50, 50), 2: (30, 40), 3: (25, 20), 4: (10, 14)*

7 EXPANDED GENERIC MODEL OF CONFLICT

When conflict is observed under the axioms of systems theory, then this is an open system. This means that it interacts with its own environment. Now many questions arise:

1. What (or better who) is the conflict environment? We will use the term 'stakeholders', which could refer to one or many.
2. How do stakeholders react to the conflict? Are they interested in resolving or at least diminishing the conflict? Or do they desire that the conflict should remain at the certain level, or even escalate?
3. How do they intervene in the conflict?
4. What is the logic behind the intervention?

The answer to all these questions depends on where the conflict arises, at which level of society, and the interests and possibilities of stakeholders.

Our aim is a generic model of conflict. So we have limited this research to organisational conflicts with only one stakeholder: management with the interest to solve or diminish the conflict.

In terms of the model we have to mimic people's reasoning. Fuzzy logic is an appropriate methodology for this. We decided to use a fuzzy rule-based inference, which we modelled in

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accordance with the systems dynamics paradigm. Our modelling approach has been inspired by Lui et al., [22,23]. The generic conflict model expanded with the fuzzy logic inference is presented in Figure 7.

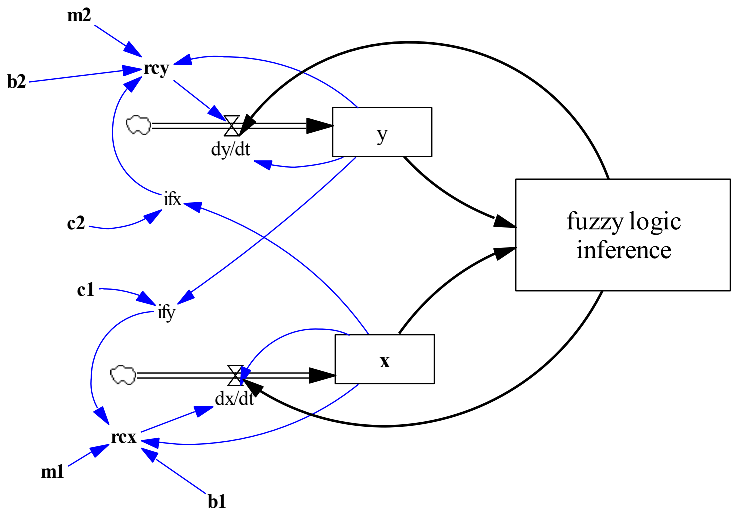

Figure 7: *Expanded generic model of conflict (stock-and-flow model)*

The detailed description of the fuzzy logic inference model, [24], is beyond the scope of this paper.

8 CONCLUSIONS

The aim of the generic model of conflict in the form of differential equations or stock-and-flow models (or even more broadly, in the form of an executable computer program) is to explain the mechanism (structure) that drives the dynamics of conflict. Conflict behaviour depends on the structural parameters *b*, *m*, and *c*, their values, and mutual relations/structure of conflict. The values of these parameters are intrinsic characteristics of the actors involved. Where the conflict will go depends on the relations between the vales of parameters, and also on the form of the initial emotional levels. As mentioned above, if the model cannot be expressed as a system of differential equations, the stock-and-flow simulation remains a convenient tool to cope with conflict dynamics. We have presented the model of conflict and we emphasised that the conflicts happen in a certain environment that both influences and is influenced by conflict. Stock-and-flow models are easy to understand, and they do not require a deeper knowledge of calculus. Such models could serve as a useful learning tool for anyone who is dealing with managing conflicts.

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ANALYSIS OF POTENTIAL RENEWABLE ENERGY SOURCES IN THE MUNICIPALITY OF PLJEVLJA IN MONTENEGRO

ANALIZA POTENCIALA OBNOVLJIVIH VIROV ENERGIJE V OBČINI PLJEVLJA V ČRNI GORI

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Keywords: renewable energy sources, hydro energy, biomass, biogas, solar energy, wind energy, Municipality of Pljevlja

Abstract

Renewable energy sources include all sources of energy obtained from natural processes, such as wind, solar energy, hydropower, biomass, and geothermal energy. They are the only inexhaustible sources of energy and simultaneously have the least detrimental effect on the environment.

This paper reports on an analysis of the potential of renewable energy sources in the municipality of Pljevlja, in Montenegro. The strategic plan is the production and use of clean energy that would have a positive impact on the environment throughout the municipality. In addition, the introduction of new technologies for the exploitation of energy resources opens the potential for new jobs. This method of managing renewable resources would enable the more efficient and healthier use of electricity.

This analysis requires the collection of current data, obtained from existing projects, and evaluating and integrating them into a whole. In addition to the analysis of the existing situation of the exploitation of renewable energy sources in Pljevlja, reasons for or against their use are also presented.

The project supports environmentally friendly technologies for the production and consumption of electricity generated from natural resources, which is urgently needed in the municipality of

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Pljevlja, because it is quite polluted due to the negative impact of the existing methods of generating electricity.

Povzetek

Obnovljivi viri energije vključujejo vse vire energije, ki jih zajemamo iz stalnih naravnih procesov, kot so veter, sončno sevanje, hidroenergija, biomasa, geotermalna energija. Oni so ne samo edini večni vir energij, ampak so za okolje tudi najmanj škodljivi.

Projekt se nanaša na analizo potencialov obnovljivih virov energije v občini Pljevlja ki se nahaja v Črni Gori. Strateški načrt je pridobivanje in poraba čiste energije, ki bi imela pozitiven vpliv na okolje v celotni občini. Poleg tega bi uvedba novih tehnologij izkoriščanja energetskih potencialov v Pljevljih odprla možnost morebitnih novih delovnih mest, kar predstavlja tudi pozitiven vidik za prebivalce. Takšen način vodstva z obnovljivimi viri bi omogočil učinkovitejšo in bolj zdravo rabo električne energije v občini Pljevlja.

Naloge sem se lotila tako, da sem predhodno zbrala podatke, ki sem jih pridobila na osnovi že znanih projektov in meritev, in vse skupaj združila v celoto. Poleg že znanih analiz trenutnega stanja izkoriščenosti obnovljivih virov energije v občini Pljevlja, so predstavljene tudi možnosti izkoriščanja le-teh v omenjeni občini, kakor tudi razlogi za ali proti izkoriščanju obnovljivih energijskih virov.

Projekt podpira okolju prijazne tehnologije proizvodnje in porabe električne energije, pridobljene na podlagi naravnih virov, kar je v občini Pljevlja nujno potrebno, iz razloga ker so Pljevlja mesto ki je precej onesnaženo zaradi negativnega vpliva dosedanjega načina proizvodnje električne energije na tem področju.

1 INTRODUCTION

When planning for the future of any country within the global economy, it is vital that each country be capable of independently meeting its energy needs. The production of energy is one of primary sources of greenhouse gas emissions; consequently, alternative (renewable) sources of energy play a key role in the production of electricity and heat with little or no CO_2 emissions. In order to reduce dependence on fossil fuels and imported energy, many countries have started programs for the exploitation and development of renewable energy sources.
The Municipality of Pljevlja is located in the north of Montenegro, near the border with Serbia on one side and the border with Bosnia and Herzegovina on the other. It is located in a valley surrounded by mountains, which impede the air flow rate. Pljevlja occupies an area of 1346 km², which represents 10% of the entire territory of Montenegro; it is the third largest municipality in the state.

Figure 1: *Characteristics of Pljevlja*

The location hinders easy transport links, and the local economy depends primarily on the thermal power plant and coal mine, which are the main sources of income and employment of citizens. Agriculture is poorly developed; other natural resources have not been sufficiently exploited, [1].

2 METHODS OF ANALYSIS

The basis of the project is collecting data obtained from existing projects, and evaluating and then grouping the date into a whole. In addition to the data collected, I have made an analysis of the full potential of renewable energy sources, as well as the extent of their utilization in Pljevlja.

Hydropower - Through the analysis of hydropower, I have concluded that Pljevlja has serious potential for drinking water and the potential for the construction of hydropower infrastructure (mainly small hydropower). In terms of the water supply, the Tara and Cehotina Rivers are significant flows. Utilization of hydropower would occur on the Cehotina River downstream from Pljevlja to the border with Bosnia and Herzegovina. The Cehotina is a tributary of the Drina River and is the northernmost river in Montenegro, with a length of 124.5 km. The estimated gross energy potential of the river is 463 GWh. To date, there have been several possibilities for exploiting the energy potential of the Cehotina River, i.e. for the construction of small hydropower plants. Regarding the current status of utilization of water resources, the beginnings of exploiting water power date back to the 1980s, when a dam was built on the Cehotina in Otilovici. The main objective was to provide sufficient water for the cooling generator units of the Pljevlja thermal power plant. Currently, it is the only hydropower plant in Pljevlja, [2].

Biomass - Pljevlja has available a certain potential of biomass that has not exploited. The total area of the municipality is 134,600 ha, of which forests and forest areas occupy 79,458 ha or 59%.

Table 1: *Capacity and agriculture statistics in Pljevlja [3]*

Capacity of agricultural land	**Surface (ha)**
agricultural	55,161
forests	**79,458**
TOTAL	134,619

The capacity of the forests in the municipality of Pljevlja is 11,394,824 m^3, of which 11,181,667 m^3 is state-owned. Among conifers, spruce is the most common at 66.6%, then fir at 21% and other conifers at 14.4% (black and white pine). Most of the entire municipal area is occupied by forests, which is a favourable condition for woodworking, the development of small enterprises processing wood, the utilization of wood waste and the processing of waste into briquettes (for heating and biomass). The largest wood processing company is called Vektra Jakic; there are also a several smaller companies. Large areas have been covered with wood waste, which is produced in the company.

Figure 2: *"Black points" of biomass in Montenegro, [4]*

In the previous fifty years, a landfill was made, containing 150,000–200,000 m^3 of wood waste, which is an "ecological bomb" that would release large amounts of carbon monoxide in case of arson and would simultaneously endanger the local environment. The enterprise Vektra Jakic is polluting the atmosphere with boiler flue gases. According to the current practice, wood waste is not disposed of properly, but is left in the open, and the incurred methane is released into the atmosphere. The issue of waste wood is a significant problem, which is usually referred to as "black points" of biomass in the municipality of Pljevlja. No system exists for obtaining energy from biomass, although given the current conditions, it would be beneficial to use such energy for home heating, [3].

Biogas - Biogas is one of the least explored potentials of renewable energy sources in Pljevlja. Currently, there is no facility for obtaining biogas. Although there is a certain amount of municipal waste and waste from agriculture, this energy source is completely ignored. In addition, the amount of waste that could be used for such purposes is not known. All this has a bad influence on residents and the municipality. Instead of obtaining environmentally friendly energy, much of this waste is discarded and disposed of in landfills outside the city, which are a serious problem for the environment. All citizens should be aware of the negative impact of landfills, primarily for the protection of the environment in which they live. It is necessary to analyse the potential and possibilities of utilization of biogas in Pljevlja, in order to enable the production of biogas and also reduce environmental pollution.

Solar energy - Pljevlja's potential in terms of solar energy is entirely unexplored. At the municipal level, as well as at the state level, no data have been obtained from measurements; consequently, there are currently no possibilities for using solar energy in Pljevlja. Not only in the municipality, but also in Montenegro, solar energy is a renewable energy source that does receive sufficient attention. Montenegro has no solar power plant. On the south of country, solar energy is used for heating water. To date, in Montenegro exist only nine public buildings equipped with solar cells and about 190 similarly equipped rural houses. However, such use of solar energy does not exist in Pljevlja. To start using solar energy, it is necessary to make accurate measurements of it, and to make plans for its proper utilization. According to the experts, the Pljevlja area probably is not suitable for the construction of solar power plants to generate electricity; however, energy can be obtained in large quantities from solar collectors for household needs and the needs of tourists, [5].

Wind energy–The Municipality of Pljevlja is not suitable for the use of wind energy, because the average wind speed is too low (0.5–0.2 m/s). Wind energy could be exploited on the mountain tops and ridges. If windmills were set up in these areas, they would be turbines for weak flow, and small for rated power. Due to the lack of data, it is difficult to assess the real potential of wind and possibilities of its utilization. Existing data are primarily from meteorological stations, where the wind measurements were not carried out at different heights and at the heights at which windmills operate. Because of this, it would be advantageous to make more detailed and accurate measurements at locations that could be appropriate for windmills. However, setting up large fields of windmills in this area would not make sense, because the wind potential is not sufficiently large to justify such a step, [6].

It can be concluded that Pljevlja exploits renewable energy sources to a very small extent (the existing Otilovici hydropower plant). The reason for this is simply the fact that the potentials remain under-explored. The main problem is the lack of funding for the development of projects, coupled with a low awareness of the citizens about the positive effects of electricity production from renewable energy sources.

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3 RESULTS AND DISCUSSION

Analysis of the potential of renewable energy sources says that they can have a highly significant role in the energy balance of the municipality, also at the state level. However, there are many obstacles that prevent wider use of renewable energy sources in Pljevlja, for example, very low prices of traditional energy sources and fuel, not enough investors interested in particular technologies, the lack of a legal basis for using renewable energy, and finally an uninformed public that is not aware of the possibilities of using the renewable energy sources.

Pljevlja is an industrial centre, which produces large amounts of energy via a thermal power plant and coal mine. However, my idea is to find an alternative that will represent a safer, more efficient more adaptive method of electricity generation.

In addition to the analysis and research potentials of renewable energy, a plan for their development in Pljevlja can also be created. Currently, hydropower and biomass energy are available. Other energy sources have not been sufficiently explored, so it is not possible to plan for their further exploitation. For the development and use of the energy potential of biomass and water, it is necessary to do a feasibility study and to make an assessment of the implementation of certain activities, both from a technical as well as an economical perspective.

Planned methods of development of renewable energy sources in Pljevlja:

- hydropower - the construction of a small and medium HPP,
- biomass – district heating project;

Hydropower

In Pljevlja, small streams are a highly important part of the hydro potential. Of all the existing small streams in Pljevlja, two have serious potentials that have been partially explored. Based on that, I set some assumptions about the possibilities of using these two streams for energy purposes. The Gotovusa River is the right tributary of the Cehotina, and at that place it is possible to build a dam. The left tributary of Cehotina is called the Rijeka. The canyon of the Rijeka River can be used for a small hydropower plant.

There is also a possibility of building medium-sized hydro power plant on the Cehotina. In all of the documents on the use of water power, the Cehotina is seen as potentially having a hydropower facility. In addition to the existing Otilovici hydropower plant, there are two more possibilities of building medium hydropower plants on the Cehotina. There are some alternative solutions that would be adapted for construction.

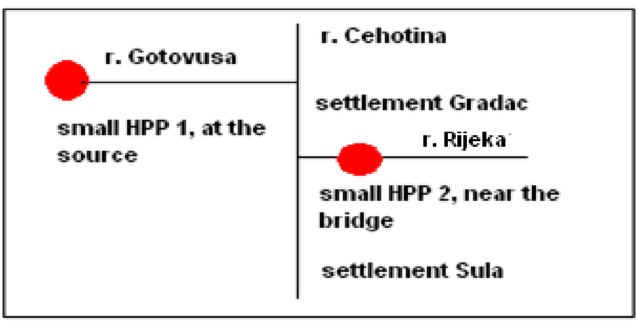

Figure 3: *Situation along the Cehotina, Pljevlja*

Variant 1: According to this variant, construction of downstream reservoirs, called Gradac and Mekote is predicted. However, if we pay attention to the amount of water in the direction of flow rate to the Drina and the possibility of building a larger tank, it would be ideal to take into account the second variant.

Table 2: *Variant 1- presentation of basic data for the HPP Gradac and HPP Mekote*

Name of HPP	Category	Length performance (km)	Q_{med} m^3/s	Q_{inst} m^3/s	H_b (m)	H_n (m)	P_i (MW)	E_{ann} (GWh/year)	V_k (hm^3)	Elevation (masl)
HPP Gradac	derivation	4.0	12.56	38	78	70	23	65.5	85	742
HPP Mekote	derivation	6.2	15.39	38	74	62	26	70.6	74	657
TOTAL							49	136	159	

Variant 2: Bearing in mind the level of the Cehotina and its high altitude position, we can conclude that below of Gradac morphological and other conditions are such that there will be greater accumulation and a rather effective solution for the use of water in a natural way; that would require the construction of the Buk Bijela reservoirs.

Table 3: *Variant 2 - presentation of basic data for the HPP Gradac and HPP Milovci*

Name of HPP	Category	Length performance (km)	Q_{med} m^3/s	Q_{inst} m^3/s	H_b (m)	H_n (m)	P_i (MW)	E_{ann} (GWh/year)	V_k (hm^3)	Elevation (masl)
HPP Gradac	derivation	3.8	12.56	38	85	77	25	72	85	742
HPP Milovci	dam		17.18	50	119	117	50	149.7	386	650
TOTAL							75	222	471	

It can be achieved with construction of the Milovci reservoir, whereby the construction of the Mekote reservoir should be omitted.

With the construction of reservoir downstream from Mekote, on the Milovci profile a greater accumulation and a greater amount of energy are obtained; moreover, there is a possibility that the water from Cehotina can be used in the direction of the Buk Bijela reservoir. The main value of the second variant is reflected in the fact that it is possible to obtain a major accumulation at Milovci (386 hm^3), which can be successfully integrated into the environment. We can see that Version 2 (Milovci hydropower plant) is better than Variant 1 (Mekote hydropower plant) for several reasons.

Biomass – district heating project

The project concerns remote heating infrastructure, which has many advantages, including economic benefits. With this example, we use biomass as fuel.

Advantages of heating with biomass:

- It is a renewable source of energy;
- it reduces pollution;
- it enables the development of new forest regions;
- it creates jobs.

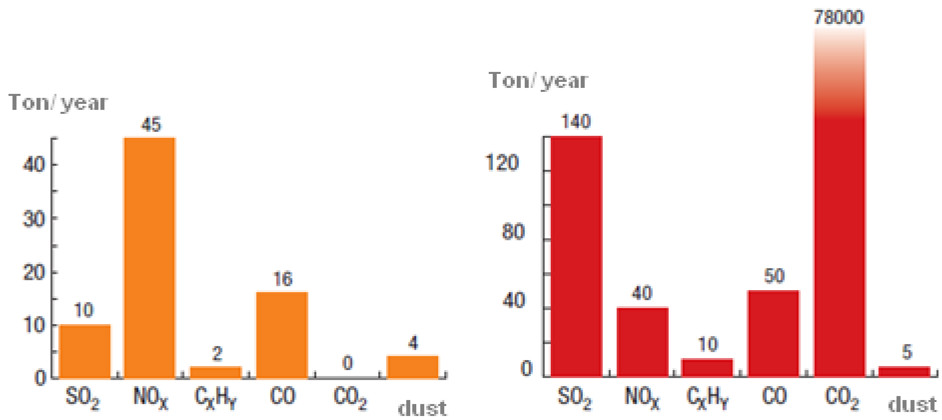

Figure 4: *Comparison of emission values in the use of biomass (left) and fossil fuels (right)*

Feasibility of the project - Currently, the heat for industry and households in Pljevlja is produced from burning coal or wood, or by electricity. Coal is the least advantageous fuel, which causes excessive pollution in winter and disrupts the ecological balance of the environment. The municipality currently provides a very low level of heating services (for ten buildings in the city centre). They are heating with outdated, inefficient boilers that are placed in garages. The furnaces are manually managed, and have unsupervised releases of gases that cause extensive air pollution. A biomass heating system in Pljevlja would increase the energy efficiency in place, visibly reduce greenhouse gas emissions and also reduce the use of electricity for heating.

Phases of the project:

- implementation of the technical works,
- implementation of the project requires significant corporate development support.

Results to be achieved:

- replacing the old heating system,
- reduction of the environmental pollution,
- improving the economic aspect,
- introduction of new products, including sales of heat.

Project organization - In places where the district heating system is not formed yet, organization of the project must start from the beginning. The aim of the first phase requires a means for

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assessing the feasibility of the project. The main investor should be the European Bank for Reconstruction and Development.

Table 4: *SWOT analysis*

STRENGTHS	OPPORTUNITIES
• additional sources of revenue for the municipality, e.g. sale of scrap; • environmentally beneficial way of heating; • compared with other fuels, heating with wood is more cost effective than with fossil fuels; • the municipality has the capacity (factories, machinery) for the production of wood products.	• the possibility of obtaining resources for co-investment; • additional revenues from promotions (trips, workshops); • expansion of district heating using wood biomass to a larger region; • with good management of the wood biomass district heating system, the municipality would gain prestige.
WEAKNESSES	**THREATS**
• in case of unsuccessful leadership, the project may affect the negative financial balance of the municipality.	• weather conditions greatly affect the demand for heat; • incorrect assessment of the demand for heat; • possible weakening of the relationship between customers and providers of heat.

<u>Timetable of activities</u> - In accordance with the plan, the implementation of the heating system would take four years. First, the project should be evaluated; then the approval of the board of directors must be obtained for the implementation of the project. Finally, it is necessary to provide financial resources that would enable planning and project duration. If the entire documentation enumerated in the first three points was obtained, then it would be possible to start the project and its implementation in a particular territory. If everything goes as planned, the project would be completed in four years.

Table 5: *Timetable of activities*

ACTIVITIES	TIME
Assessment of the project	1st half of the first year
Approval of the board of directors	2nd half of the first year
Loan contract	By the end of the first year
The beginning of the project	The beginning of the second year
The end of the project	The end of the fourth year.

Investment part of the project

- EBRD (European Bank for Reconstruction and Development),
- the municipality of Pljevlja;

The main contributor would be the Vektra Jakic wood processing plant.

Demand for heat

The most important task of examining the feasibility of the project is to evaluate heating requirements, which depend of the number of users, regarding the revenue we expect in the final stage.

Table 6: *Before and after the installation of a biomass boiler*

	Number of existing boilers	Number of individual coal stoves	USE OF BIOMASS **(tons)**	Maintenance (€)	CO_2 emissions (tons)
Current state	18,345	69,455	-	10,000	33,359
After installation of a biomass boiler	-	-	32,941	10,000	371

Assumptions about prices of energy

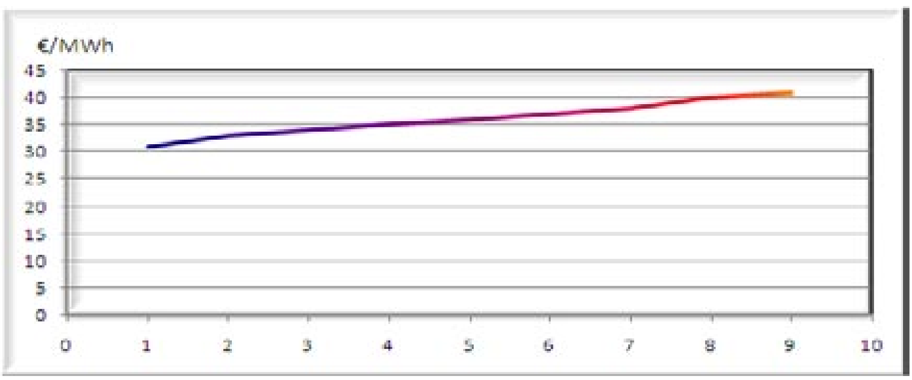

Figure 5: *Display of price growth in the following period*

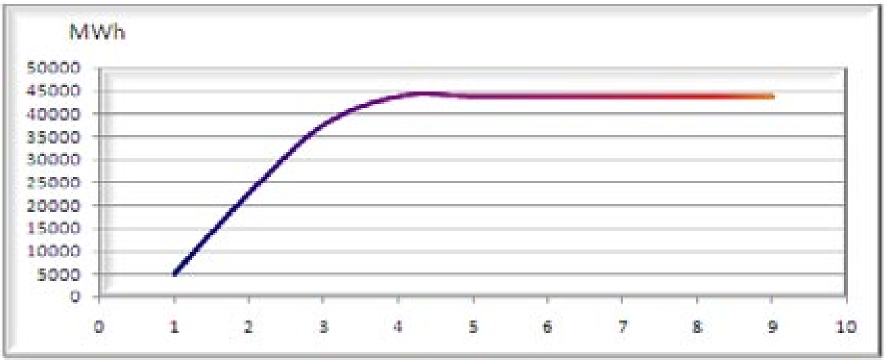

Figure 6: *Sales of heat from the district heating system*

<u>The ratio of financial costs and anticipated savings, time feasibility of project</u>

The costs of the financing of priority investments consist of debts, interest and compensation for debt financing, as well part of the financial capital. When the negative elements of cash flow are compared with the projected income, it is possible to calculate the time of repayment. The time when the project will be paid off is longer than the total project duration. Roughly, it would be 15 to 16 years from the establishment of the project.

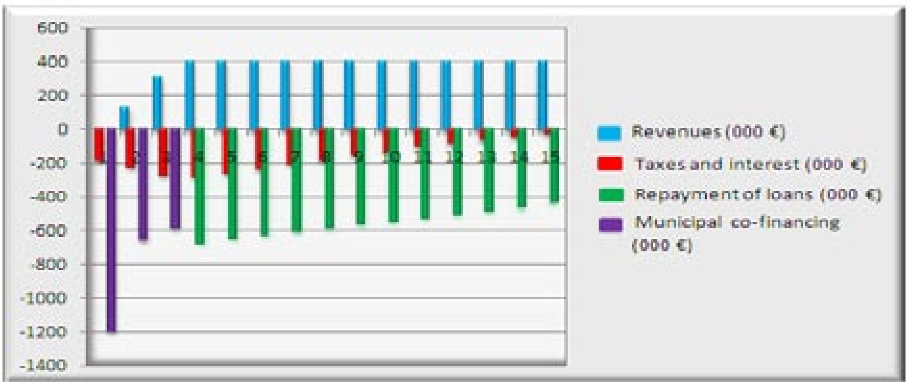

Figure 7: *The cost of financing and the anticipated savings*

<u>Additional comments on the project *(duration, limitations, assumptions, risks, etc.)*</u>

It is estimated that implementation of the project would take three to four years. The constraints that might arise in such a project are primarily financial.

Table 7: *Assumptions about the total investment costs*

PROJECT	INVESTMENT COSTS (€)
Total investment costs (distribution network, heating equipment, biomass boiler)	ca. 6,000,000
Total project costs (investment costs, technical assistance)	ca. 6,600,000

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4 CONCLUSION

Lack of funding and low awareness of the benefits of generating energy from renewable sources are the main culprits behind the poor use of these resources in Pljevlja. The municipality is supplied with electricity from a thermal power plant and therefore suffers negative consequences in the form of pollution. Use of the existing potentials of renewable energy sources would have a positive impact on the environment throughout the municipality. Moreover, the introduction of new technologies for the exploitation of energy resources in Pljevlja would open the possibility of new jobs, which is another positive aspect for citizens. This way of managing renewable energy sources would enable the more efficient and healthier use of electricity in Pljevlja.

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POSSIBILITIES FOR ENERGY EXPLOITATION OF LANDFILL GAS FROM OLD MUNICIPAL SOLID WASTE LANDFILLS IN SLOVENIA

MOŽNOSTI ENERGETSKEGA IZKORIŠČANJA DEPONIJSKEGA PLINA IZ STARIH ODLAGALIŠČ KOMUNALNIH ODPADKOV V SLOVENIJI

Jože Kortnik[ℜ]

Keywords: greenhouse gas emissions, landfill gas (LFG), landfill gas power plant, municipal solid waste landfill (MSW), non-dangerous waste

Abstract

In Slovenia, landfill gas is presently exploited at only fifth municipal solid waste (MSW) landfills. Practice has shown that the installation of facilities for the exploitation of landfill gas for producing electrical energy is cost-efficient only at those landfills that collect over 60,000 tons or m³ of waste annually. A quick calculation for Slovenia shows that the use of landfill gas in gas-operated generators could be done at 17, not merely 10 MSW landfills (and it is presently done at only 4). In this way, Slovenia could quickly achieve the prescribed 21% of electrical energy from renewable energy sources by the year 2020 (which presently ranges between 18% and 19%). Although there is a possibility of cost-efficient exploitation of landfill gas even at smaller MSW landfills, which receive from 20,000 to 60,000 tons of municipal solid waste per year, in the case of smaller gas-operated generators (143 kWe) that require more demanding maintenance and the need to construct an additional system for active landfill degassing, such investments may be at the limit of profitability. This paper presents potentially generated

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quantities of landfill gas and assesses the possibilities for energy exploitation of landfill gas from the already closed old non-hazardous waste deposits at Leskovec and Bukovzlak, using the LandGEM software package.

Povzetek

V Sloveniji se deponijski plin danes izkorišča na štirih lokacijah odlagališč nenevarnih odpadkov. V Sloveniji bi lahko izkoriščanje deponijskega plina v plinskih agregatih v Sloveniji potekalo kar na 17, namesto na samo 10 odlagališčih komunalnih odpadkov (danes poteka samo na 5 odlagališčih). To bi lahko Slovenija hitreje dosegla zahtevan cilj glede doseganja 21 % deleža pridobljene električne energije iz obnovljivih virov do leta 2020 (danes med 18 in 19 %). V praksi je uveljavljeno pravilo, da je postavitev objektov za energijsko izrabo deponijskega plina ekonomsko upravičena le na odlagališčih, ki sprejmejo več kot 60.000 t oz. m^3 odpadkov letno. Kljub temu, da obstaja možnost ekonomske upravičenosti izrabe deponijskega plina tudi v primeru manjših odlagališč z 20.000 do 60.000 t/leto odloženih količin komunalnih odpadkov, je lahko investicija v primeru zahtevnejšega vzdrževanje manjšega plinskega agregata (143 kWe) in potrebne dodatne izgradnje sistema aktivnega odplinjevanja lahko na meji rentabilnosti. V članku je podana ocena in možnosti energetskega izkoriščanja deponijskega plina iz danes že zaprtega starega odlagališča nenevarnih odpadkov Leskovec in starega odlagališča nenevarnih odpadkov Bukovžlak s programskim paketom LandGEM.

1 INTRODUCTION

Due to the negative effect of landfill gas on the atmosphere and ground water, its use for the purpose of power supply is increasingly important and also cost-efficient. This is evident from many examples of its use in EU member states and throughout the world, [1].

In accordance with Directive 2001/77/EU, by the year 2010, all EU member states were required to cover about 12% of their power supply needs from renewable energy sources, including landfill gas. In Slovenia, this goal was not achieved and, based on the current trends, this value is between 18% and 19%. The EU supports all systems for using renewable energy sources through tax relief, green certificates and specific tariffs for electrical energy production; it also encourages and stimulates investments into such programs [2].

The exploitation of landfill gas at closed and new MSW landfills requires the construction of systems for collecting landfill gas and the prompt shielding of waste with appropriate coverage or by installing a suitable covering layer. Practice has shown that the installation of facilities for the exploitation of landfill gas for power supply purposes is cost-efficient only at landfills that are able to collect over 60,000 m^3 of waste annually.

2 MUNICIPAL WASTE MANAGEMENT IN SLOVENIA

The first strategic orientations for waste management in Slovenia, which are an integral part of the National Environmental Protection Program, were prepared in 1996. The current situation and problems in the field of waste management in Slovenia also include the general method of removing waste from its place of origin and its subsequent deposition at more-or-less controlled landfills. The operative waste disposal program, with the goal of reducing the quantities of deposited biodegradable waste, which was initially prepared for the period from 2004 to the end of 2008 and was supplemented in March of 2008, is an important strategic document and will remain in force until the end of 2013. In Slovenia, about 912,981 tons of waste were deposited at municipal waste landfills in 2009; i.e. 449 kg of municipal waste were created per capita per year (1.23 kg per capita per day); this is about 13% below the EU-27 average. Municipal solid waste comprises about 35% to 40% of organic waste, and according to some data the quantity of all biodegradable waste is up to 60%. Based on European requirements, the amount of municipal waste deposited at Slovene MSW landfills should have been reduced by 20% by the year 2010 compared to the year 2000, but this goal was not attained.

Table 1: *Quantities of municipal solid waste produced in Slovenia and the EU (kg per capita), source:EUROSTAT (http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do;jsessionid=9ea7d07e30d77f896c3db973483d8c3b9940ce3d128a.e34MbxeSahmMa40LbNiMbxaMbNaMe0 (retrieved 24.04.2013))*

Year/Amount	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
EU-27 (kg/capita)	526	514	513	515	521	522	519	509	507	503
Slovenia (kg/capita)	407	418	485	494	516	525	542	524	490	411
Slovenia (kg/capita)*	411	402	417	422	430	437	453	449	422	352
Slovenia (1000 t/year)	812	834	969	989	1,036	1,060	1,095	1,069	1,004	844

* source: SURS (http://www.stat.si/eng/novica_prikazi.aspx?id=4244)

In 2009, there were 61 waste landfills in Slovenia, including 14 industrial waste landfills, 47 MSW landfills and one hazardous waste landfill. The regional concept of waste management dictates that from 15 July 2009 onward, within the framework of the prescribed 15 waste regional centres, only those Slovene landfills are allowed to operate that have acquired a specific permit in accordance with the EU Directive on Integrated Pollution Prevention and Control (IPPC). With the environmental protection permit issued by the Slovenian Environmental Agency (ARSO/SEA), there are presently six MSW landfills in Slovenia (Figure 1), but a total of 21 MSW landfills are currently still in operation without this permit and will have to cease operations soon or their managers risk a fine of €10,000. The Environmental Inspectorate may also repeat this sanction until landfill managers obtain the said environmental protection permit.

Figure 1: *MSW landfills in Slovenia with monthly deposited quantities of municipal solid waste (MSW) in tons, source: Delo, April 2012.*

At the 27 current MSW landfills that are still in operation, less than 20,000 tons of municipal solid waste are deposited annually; at 10 there are between 20,000 and 60,000 tons of deposited municipal solid waste, and at a further 10 (including all four landfills already possessing the environmental protection permit) there are over 60,000 tons of deposited municipal solid waste (Figure 1) from which the exploitation of landfill gas using gas-operated generators would be possible.

For biodegradable waste, the Decree on the Landfill of MSW (Official Gazette, No. 32/06) lays down the permitted quantity of biodegradable components in MSW that may be landfilled within Slovenia (Table 2).

Table 2: *The quantity of biodegradable components in municipal waste that may be disposed annually at all MSW landfills in Slovenia, source: Official Gazette, No 32/06)*

Period	Reduced annual quantities of disposed biodegradable MSW, expressed through reduction of the % of biodegradable waste in MSW generated in 1995	Annual quantity of disposed biodegradable substances in MSW, expressed as a % of the mass of MSW generated in 1995	Annual quantity of biodegradable components in disposed MSW
	(%)	(%)	(in 1.000 t)
Base year 1995		63	445

2001	5	60	423
2002	5	57	401
2003	5	54	378
2004	5	50	356
2005	5	47	334
2006	5	44	312
2007	10	38	267
2008	10	32	223
2012	5	28	200
2016	5	25	178

3 EXPLOITATION OF LANDFILL GAS IN SLOVENIA

Landfill gas exploitation becomes possible when the percentage of methane exceeds 35 vol.%. The exploitation of the energy value of landfill gas is possible through its incineration for various heating processes (e.g. steam or hot water production) and this is the most favourable approach from the thermodynamic standpoint. If there are no appropriate thermal energy consumers in the vicinity of the landfill site (1 to 2 km), it makes sense to exploit landfill gas to produce electrical energy with gas-operated generators. However, for energy exploitation of landfill gas to be possible, the percentage of methane should be at least 40 vol.%. The calorific value of landfill gas containing 50% of methane is about 18.8 MJ/Nm^3 = 5.2 kWh/ Nm^3 and the calorific value of natural gas is 38.4 MJ/Nm^3. At landfill gas powers of over 1,000 kW, the use of gas-operated generators (turbogenerators) having a thermodynamic coefficient of 28% efficiency is sensible, while that of gas engines is only around 25%. The actual coefficient of efficiency of a gas engine depends primarily on its load and it decreases with a reduction in the gas-operated generator load.

In Slovenia, landfill gas is exploited at five non-hazardous waste landfills (Table 3), specifically at small gas-operated power plants of Barje, Pobrežje, Dogoše, Bukovžlak and Tenetiše.

Table 3: *Power of generators for the exploitation of landfill gas at Slovene landfills.*

Landfill	Aggregate power installed	Rated electric power*	The annual production of electricity
Barje	(1996) 2 × 625 kWe (2007) 2 × 1,063 kWe 1 × 867 kWe 4,243 kWe	2,702 kWe	6,595 MWh (1996) 1.8 MW heat power
Pobrežje	(2001) 630 kWe	625 kWe	4,665 MWh (2004) 4,500 MWh (2005)

			5,000 MWh (2008) 2,000 MWh (2010)
Dogoše	(2012) 330 kWe	330 kWe	2,500 MWh (2012)
Bukovžlak	(2002) 625 kWe (2007) 1,063 kWe 1,688 kWe	1,669 kWe	8,400 MWh
Tenetiše	(2010) 469 kWe	469 kWe	Np
Total	7,360 kWe	5,795 kWe	

* Source: Energy Agency of the Republic of Slovenia (www.agen-rs.si) [5].

In Slovenia, the most widely used gas-operated generators are those manufactured by Jenbacher, having nominal powers of 625 kWe, 836 kWe and 1,048 kWe, but Jenbacher generally manufactures gas-operated generators having the following nominal powers: 143 kWe, 330 kWe (Figure 2), 511 kWe, 625 kWe, 836 kWe, 1,048 kWe, 1,413 kWe and 1,698 kWe.

Figure 2: *Small gas-operated power plants at the MSW landfill Dogoše [4].*

The maximum number of operating hours of a gas engine is about 90,000 hours, i.e. operating about 10 years at an 88% working efficiency.

Based on data about annually collected quantities of landfill gas estimated using a different mathematical models, it is possible to select the necessary power and number of gas-operated engines to attain their maximum load (i.e. maximum landfill gas flow).

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4 MODELS FOR CALCULATING LANDFILL GAS QUANTITIES

Gas emissions (primarily those of CH_4 and CO_2) from landfill gas to air can be estimated using numerous mathematical models and software packages. In the EU, the following are the most widely used:

- German EPER method,
- Landfill Emission Model (LandGEM).

The German EPER method is based on the TIER-1 IPPC proposal. Depending on the degradability of waste, the annual quantities of methane and carbon dioxide emissions from landfills (controlled, uncontrolled, and with or without controlled degassing) can be calculated from the mass of deposited waste per year using the following equation

$$S_{P,Y} = Q_Y \cdot DOC \cdot DOCF \cdot F \cdot k \cdot A \cdot e^{-k \cdot \Delta t} \tag{4.1}$$

where $S_{P,Y}$ is the annual methane emissions in the year P [kg]; Q_Y is the total amount of waste deposited in the year Y (kg); *DOC* is the percentage of degradable organic carbon in the waste (%); *DOCF* is the percentage of organic carbon in the waste that is converted to landfill gas (%); *F* is the percentage of methane in landfill gas (%); *k* is the annual rate of waste degradation ( ); *A* normalization constant calculated on the basis of time in which all biodegradable waste components are degraded (for degradation in 50 years at k = 0.05, A = 1.3); the percentage of uncollected or biologically oxidized methane CH_4 also depends on the landfill type (covered, uncovered), efficiency of degassing, etc., ( ); and Δt is the time from deposition of waste in year Y until degradation in year P (year).

The greatest shortcoming of the EPER method lies in the fact that it yields precise results only when the quantity of waste deposited at a landfill remains unchanged from year to year. The selection of appropriate parameters is also problematic. This especially refers to constant A, which primarily depends on the efficiency of degassing, the gas-permeable and sealing layers, vegetation, waste compression, etc. Its value can range from 0.1 to 1.

The Landfill Gas Emission Model (LandGEM) is a software package developed by the Control Technology Center (CTC) of the U.S. Environmental Protection Agency (EPA), [3]. Its calculations are based on data about the annual quantities of deposited waste and various parameter settings (CH_4 and CO_2 content in landfill gas, degradation constant, amount of CH_4 generated from the degradation of 1 ton of waste, landfill type, planned year of landfill closure, etc.). The mathematical model of the LandGEM software package uses the following equation for the first phase of degradation of organic substances in the waste.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0,1}^{1} k \cdot L_0 \cdot \left(\frac{M_i}{10} \right) \cdot e^{-k \cdot t_{ij}} \tag{4.2}$$

where Q_{CH4} is the methane generation in time t [m^3/year]; *i* is the one year − time of increase (year); *n* is the year of calculation ( ); *j* is the 0.1 year − time of increase (year); *k* is the methane generation rate constant ($year^{-1}$); L_0 is the potential methane generation capacity (m^3/t); M_i is the mass of waste received in year i (t); and t_{ij} is the year of j-th part of mass of waste M_i received in i-th year (decimal years, e.g.: 3.2 year) (t)

LandGEM uses the following basic parameters:

- Specific data for the particular landfill,
- The CAA's set of assumed values as determined by the Clean Air Act (CAA),
- The AP−42 set of assumed values for average quantities of generated gas at US landfills issued by the U.S. Environmental Protection Agency in its publication 'Compilation of Air Pollutant Emission Factors Ap-42'.

LandGEM enables the use of various annual quantities of waste deposited during landfill operation, the estimation of the emissions of generated landfill gases, such as methane and carbon dioxide as well as various non-methane organic compounds, the calculation of the total quantity of landfill gas emissions, and the prediction of emitted quantities of waste substances several years in advance. The possibility of using different annual quantities of deposited waste throughout the period of landfill operation and setting different parameters of waste degradation enables the calculation of numerous data on generated landfill gases and thus promotes its widespread use.

5 EXAMPLES OF POSSIBLE EXPLOITATION OF LANDFILL GASS

The calculation of potential landfill gas quantities was done using the LandGEM software package. It was performed for two old, already closed MSW landfills at Leskovec and Bukovzlak. Figure 3 shows the trend of waste deposition for the Leskovec MSW from 1992 to 2007. During the period of its operation, about 23,381 tons of waste on average were deposited at the landfill each year. Since 2007, no waste has been deposited and the landfill is now closed.

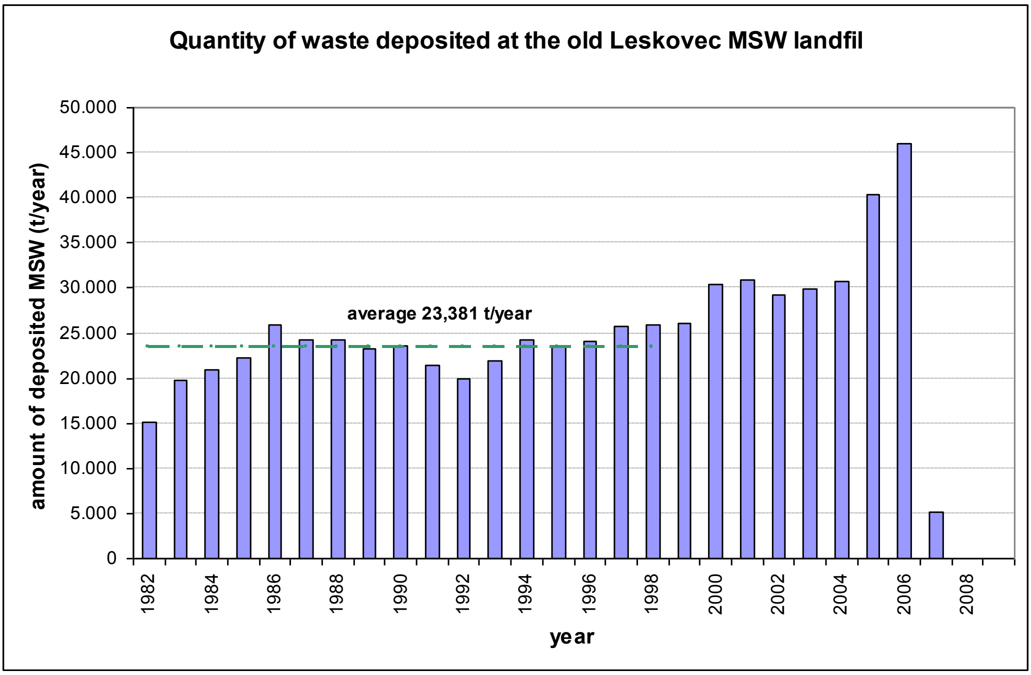

Figure 3: *Quantity of waste deposited at the old MSW landfill Leskovec per years [2].*

Based on the available quantity of methane in landfill gas, Figure 4 speaks in favour of the use of a gas-operated 143 kWe generator from 1996 to 2025. During this period and based on the 10-year anticipated life of a gas-operated generator, three gas-operated generators would probably be used over various time periods, generating a total of 37,380 MWh of electrical energy. An approximate calculation of the costs for the purchase and maintenance of a gas-operated generator and the potential revenue created with the sale of so-called 'green electricity' thus yields a profit of about EUR 2.5 million.

The calculation of the quantity of generated landfill gas at the old Leskovec MSW landfill is additionally confirmed by data obtained by measuring the actual quantities of generated landfill gas at the old Bukovžlak MSW landfill (Figure 5) for a comparable deposited waste quantity (on average 26,036 tons per year from 1972 to 2000).

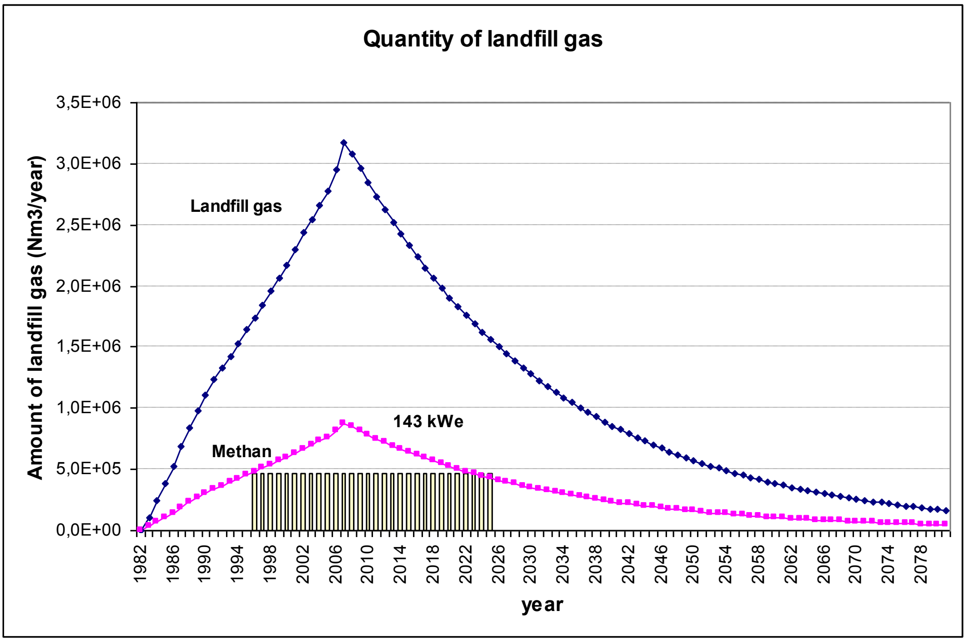

Figure 4: *Calculated quantity of landfill gas and exploitable percentage of methane (taking into account a 50% loss) at the old Leskovec MSW landfill using the LandGEM software package, [2].*

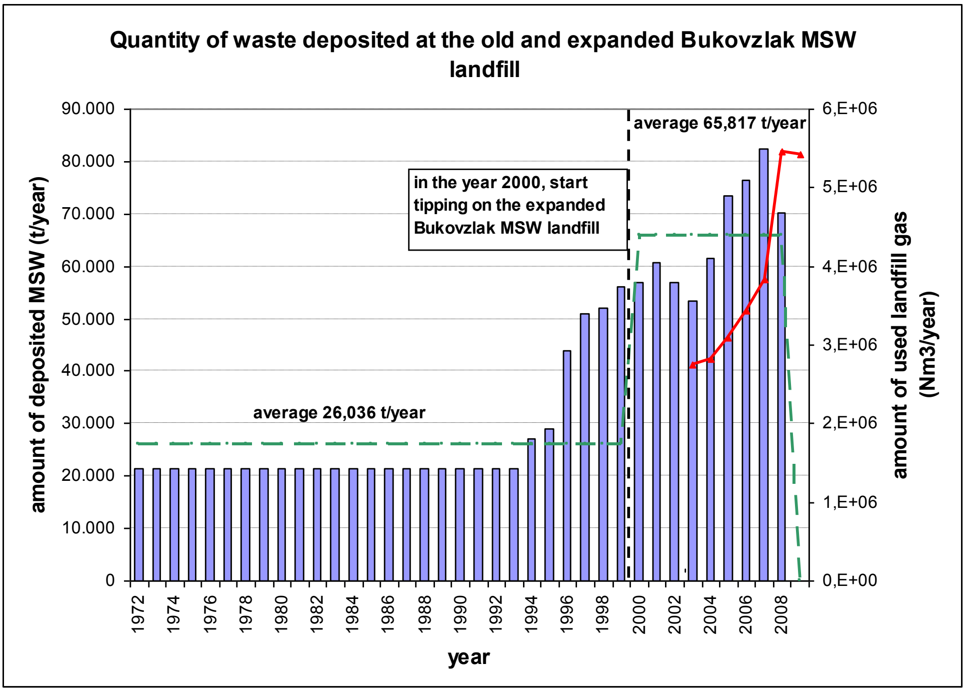

Figure 5: *Quantity of waste deposited at the old and expanded Bukovžlak MSW landfill (columns) and quantity of landfill gas used in gas-operated generators (curve) from 2003 to 2009.*

6 CONCLUSIONS

To achieve an effective turbogenerator power of 143 kWe (taking into account a 25% thermodynamic efficiency in the production of electrical energy) for delivering electrical energy to the power supply network, the landfill gas power at turbogenerator inlet should be about 572 kW (1 kWh = 3,600 kJ). At a thermal value of landfill gas of LHV_{LFG} = 18,000 kJ/Nm³ or 18.000 kJ/Nm³/3,600 kJ/kWh = 5 kWh/Nm³ 572 kW/5 kWh/Nm³ = 114.4 Nm³/h of landfill gas would be needed at the generator inlet. If the calculation is done on the basis of an established situation at a waste landfill aged 10 years at a minimum, then for assuring effective generator power of 143 kW the annual input of waste at an average TOC content should be at least 20%.

An approximate calculation made with the use of the LandGEM software package can assist in strategic planning and in the search for possibilities for the exploitation of landfill gas energy. A quick calculation for Slovenia shows that the use of landfill gas in gas-operated generators could be done at 17 and not only 10 MSW landfills (and it is presently done at only four). In this way, Slovenia could quickly achieve the prescribed 21% of electrical energy from renewable energy sources by the year 2020 (which presently ranges between 18% and 19%). Although there is a possibility of cost-efficient exploitation of landfill gas even at smaller MSW landfills that receive from 20,000 to 60,000 tons of municipal solid waste per year, in the case of smaller gas-operated generators (143 kWe) that require more demanding maintenance and the need to construct an additional system for active landfill degassing, such investments may be at the limit

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of profitability. This is because in addition to having a gas-operated generator for electrical energy production, it would also be necessary to ensure the pumping and incineration of landfill gas for the case of gas engine failure, other failures or occasional excess landfill gas emissions.

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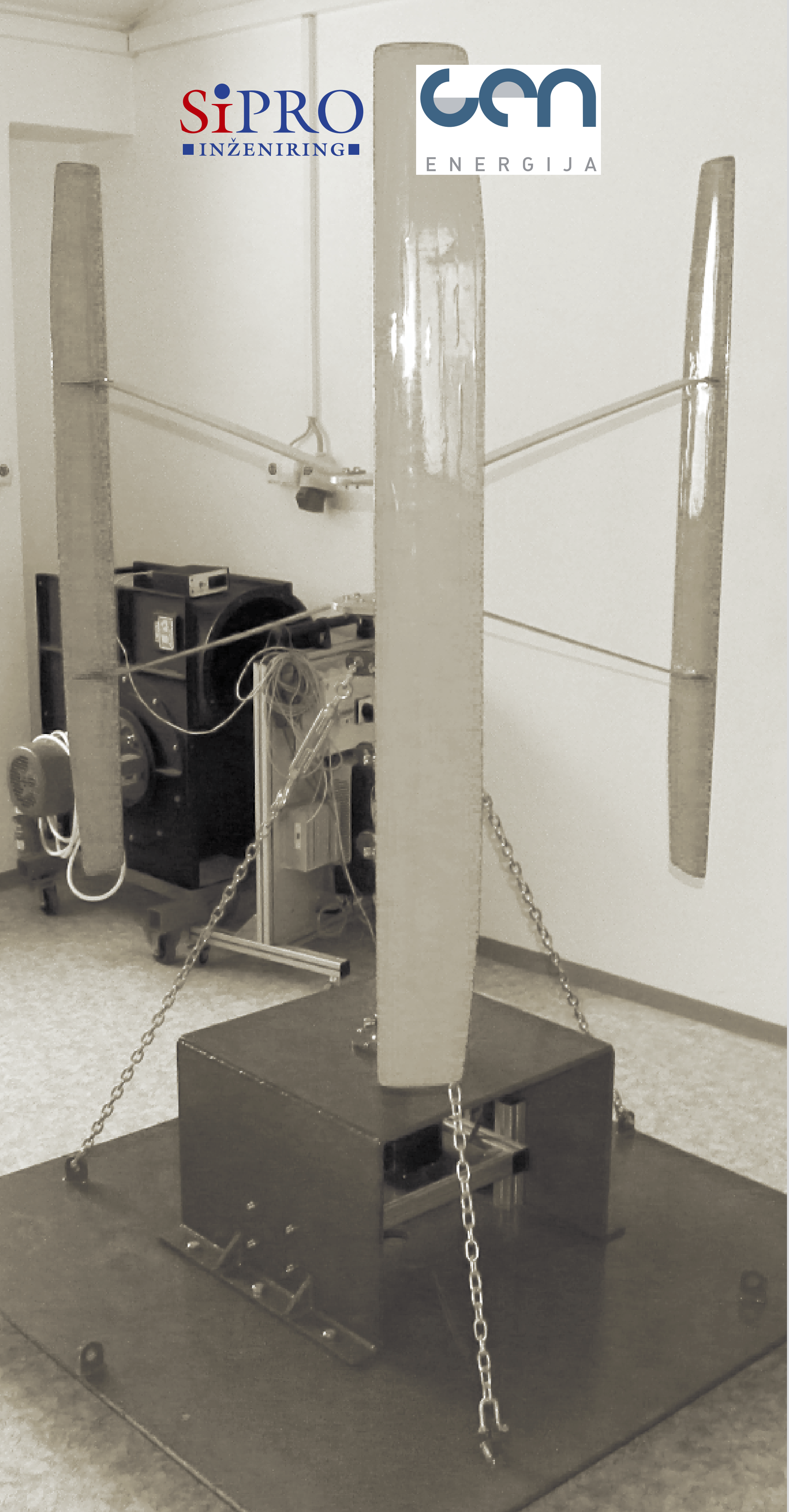

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